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Conceptual Design of a Monitoring System for the Charters of Freedom

March 15, 1984

Prepared for

National Archives and Records Service

Through an Agreement with

National Aeronautics and Space Administration

by

Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California

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16. Abstract

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The monitoring system is required to optically detect and measure deterioration in documents that are permanently encapsulated in glass cases. An electronic imaging system with the capability for precise photometric measurements of the contrast of the script on the documents can perform this task. Two general types of imaging systems are considered (line and area array), and their suitability for performing these required measurements are compared. A digital processing capability for analyzing the electronic imaging data is also required, and several optional levels of complexity for this digital analysis system are evaluated.

The conclusion of this study is that it will be possible to monitor the condition of the Charters of Freedom successfully with an electronic imaging system. Further work is needed to refine design parameters that will lead to the completion of a task implementation plan for the program.

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ACKNOWLEDGMENT

Contributors to this report included J.A. Cutts (Task Manager), T.K. Bursch, J.R. Druzik (Consultant), D.L. Glackin, B.A. Houghton, E.A. Miller, D.D. Norris, C.E. Pettus, T.H. Reilly, S.L. Wheelock, and W. Willis.

CONTENTS

SECTION I

INTRODUCTION

This report describes the Conceptual Design of a monitoring system for the Charters of Freedom. The Conceptual Design was developed by the Observational Systems Division of the Jet Propulsion Laboratory (JPL) under contract to the National Archives and Records Service (NARS).

JPL was contracted to develop a conceptual design for a monitoring system incorporating new technology, following a recommendation of the NARS Advisory Committee on Preservation that "experts in photographic methods, image analysis and non-destructive analysis should be consulted regarding the application of new technology to the documentation of the condition of the Charters and analysis in the current encasement of the inks and other document materials" (Reference 1-1).

The intention was to incorporate techniques based on new technology into "an annual program of systematic visual inspection and written documentation of the condition of the Charters by conservators familiar with parchment documents (which) should be instituted."

The JPL approach to the Conceptual Design task was to carry out an Experimental Measurements Program using a parchment document of the same period as the Charters, which was written on with similar inks and exhibited parchment defects and damage of the kind that the Charters might experience. Because the documents had to be examined within the current encasement, it was also necessary to assess the difficulty of performing monitoring measurement through a material (glass) that was also subject to deterioration and contamination of its interior and exterior surfaces.

Subsequent to the Experimental Measurements Program, a conceptual design activity was initiated. This document activity describes the results of that conceptual design phase. An implementation plan for the conceptual design is also in preparation.

Following contract award, JPL originally reported to NARS on its plans for an Experimental Measurements Program on October 1, 1982 (Reference 1-2). After completion of these measurements, JPL reported preliminary results (References 1-3 through 1-5). Following more detailed analysis of the experimental results and an evaluation of techniques for detecting subtle changes in documents, JPL reported to NARS on the Conceptual Design. This report is a narrative description of some of the material given at that presentation and action items that emerged from the presentation. This Conceptual Design report forms the basis of

an Implemetation Plan and a Detailed Design Activity planned to follow it.

REFERENCES

1-1. Report of the Ad-hoc Charters Committee of the NARS Advisory Committee on Preservation, August 3, 1982.

1-2. Presentation Materials on System to Assess the State of Preservation of the Charters of Freedom, Preliminary Experimental Measurements Plan Presented by James A. Cutts and David D. Norris to NARS, October 1, 1982.

1-3. Presentation Materials on System to Assess the State of Preservation of the Charters of Freedom, Preliminary Results of Experimental Measurements Program, January 13, 1983.

1-4. <u>System to Assess the State of Preservation of the Charters of Freedom: First Quarterly Report</u>, December 17, 1982.

1-5. Presentation Materials on Conceptual Design of a Monitoring System for the Charters of Freedom, presented by JPL Observational Systems Division to NARS, June 22, 1983.

SECTION II

EXPERIMENTAL MEASUREMENTS PROGRAM

A. OBJECTIVES

To study the properties of parchment documents and the glass containment case, an experimental measurements program has been conducted in the Observational Systems Division of JPL. The objects studied were the Petition and Memorial of Freemen (PMF) document and the glass case sample, both on loan from NARS and representative of the actual Charters of Freedom documents and their containment cases.

A program of film photography at both macro and micro scales was carried out to obtain a comprehensive set of images for planning of the electronic photography and to gain experience in the handling of fragile parchment documents. A conservation examination was undertaken by James Druzik of the Los Angeles County Museum of Art to determine how the PMF should be mounted for electronic photography and to further identify specific areas of interest for that photography. A program of electronic photography was performed to determine how such a document should be imaged and to provide a data base of digital images to be used in the image-processing analysis. The PMF document was placed on a specially constructed mounting structure and imaged with a Charge-Coupled Device (CCD) camera. An associated image-display system allowed immediate verification of image quality. The images were processed, calibrated, and analyzed in the Image Processing Laboratory (IPL), with the goal of identifying existing techniques that could be used to measure ink fading and flaking. Finally, optical measurements of the glass case sample were made to ascertain its transmission and scattering properties.

The precautions taken in handling the document and the experimental measurements and conservation examination performed are described below.

B. HANDLING PROCEDURES

During the entire period that the PMF document and the glass case sample were on loan to JPL, every precaution was taken to ensure their safety and preservation. The document was handled according to the procedures defined by JPL's Quality and Assurance Reliabilty Office. These procedures were based on the NARS document, "Requirements for the Loan of Original Records from the National Archives."

At least two cognizant engineers were with the document each time it was photographed or examined. At all other times it was locked in a limited-access vault. Handling and movement of the

document were kept to an absolute minimum. Lint-free cotton gloves and acid-free ragboard were used whenever the document was handled. Great care was exercised in unpacking, unfolding, packing and folding the PMF. A portion of the first photographic session was devoted to familiarization with the handling of parchment documents in general and this document in particular.

A humidifier was set up in the Space Telescope Sensor Test Set (STS) laboratory where the electronic photography of the document was planned and executed. Relative humidity and temperature were monitored by a recording hygrometer-thermometer for four days to establish confidence in maintaining a relative humidity of 50%, $\pm 4\%$; and a temperature of $70^{o}F$, $\pm 4^{o}$. Temperature, humidity, and ambient lighting were all carefully maintained within the set specifications.

A mount for the document was designed by the JPL Optical Sciences Group for the purpose of supporting the PMF during electronic photography. It was made of acid-free cellotex fiberboard, hinged to fold at locations corresponding to the two folds in the PMF. Mylar envelopes were made to secure each end of the document but still permit sufficient freedom of motion. Bands of wrapped polyethylene were used at selected intervals to hold the rest of the document to the board. The envelopes and bands were pushpinned to the board. The mounted PMF was moved through all planned positions very carefully to check for stress on the document.

Once the preceding safety and handling precautions were established, the following experimental measurements and examinations were made.

C. FILM PHOTOGRAPHY

The first photographic session was held on November 1, 1982. Part of the session was devoted to familiarization with handling procedures for the PMF. The remainder of the session involved large-format, overall photography of the document. Black-and-white and color photographs were obtained with 4 x 5 and 8 x 10-in. film to help select specific areas of interest for detailed study. In particular, examples of faded ink, flaked ink, different colors of ink, foxing, stitching, leather marks, and staining were noted. The document was measured for mounting.

During the second photographic session on November 4, 1982, the identified areas of interest were photographed at both macro and micro scales, in black and white and in color. These images provided the basis for planning the electronic photography, served as orientation references during that photography, and provided insight into the film structure of the parchment and the detailed nature of ink flaking. Measurement of penstroke width

on these photographs gave an indication of the range of spatial resolution that should be examined during electronic imaging.

The PMF was brought to the JPL Photographic Laboratory for the last time on November 12, 1982, to install a small hygrometer-thermometer into the foam core frame next to the document. Windows were cut in all subsequent packaging layers so that readings could be taken while the PMF was still in the package. A chart-recording hygrometer was placed in the vault with the PMF.

D. CONSERVATION EXAMINATION

A conservation examination of the PMF was conducted to document its condition and to further identify specific areas of interest for electronic photography. The following types of problems were found: insect/mechanical damage, fading and/or color shifts in different inks, flaking of inks, stress-dependent deformations, soiling, trimming, micro-biological discoloration, foxing, large area yellowing, large skin imperfections, and old folding lines. Four characteristics were identified that can be considered unstable under adverse conditions and hence important to image: fading, flaking, parchment splitting, and movement in regions of stitching. Results of the conservation examination are described in Appendix A.

E. ELECTRONIC PHOTOGRAPHY

1. Introduction

Experimental electronic photography of the PMF document was performed during November 1982, using the Space Telescope Sensor (STS) Test Set at JPL and a CCD camera.

2. Experimental Equipment

The STS consists of the following equipment:

(1) A large optical table that supports the CCD camera, its readout electronics, light sources, targets, etc. (Figure 2-1).

(2) A liquid nitrogen cooling system for the CCD.

(3) Associated computer and image-processing hardware and software that are used to acquire images, assess their quality, store them, and produce hard copies (Figure 2-2).

The detailed image-processing analysis was performed in JPL's Image Processing Laboratory.

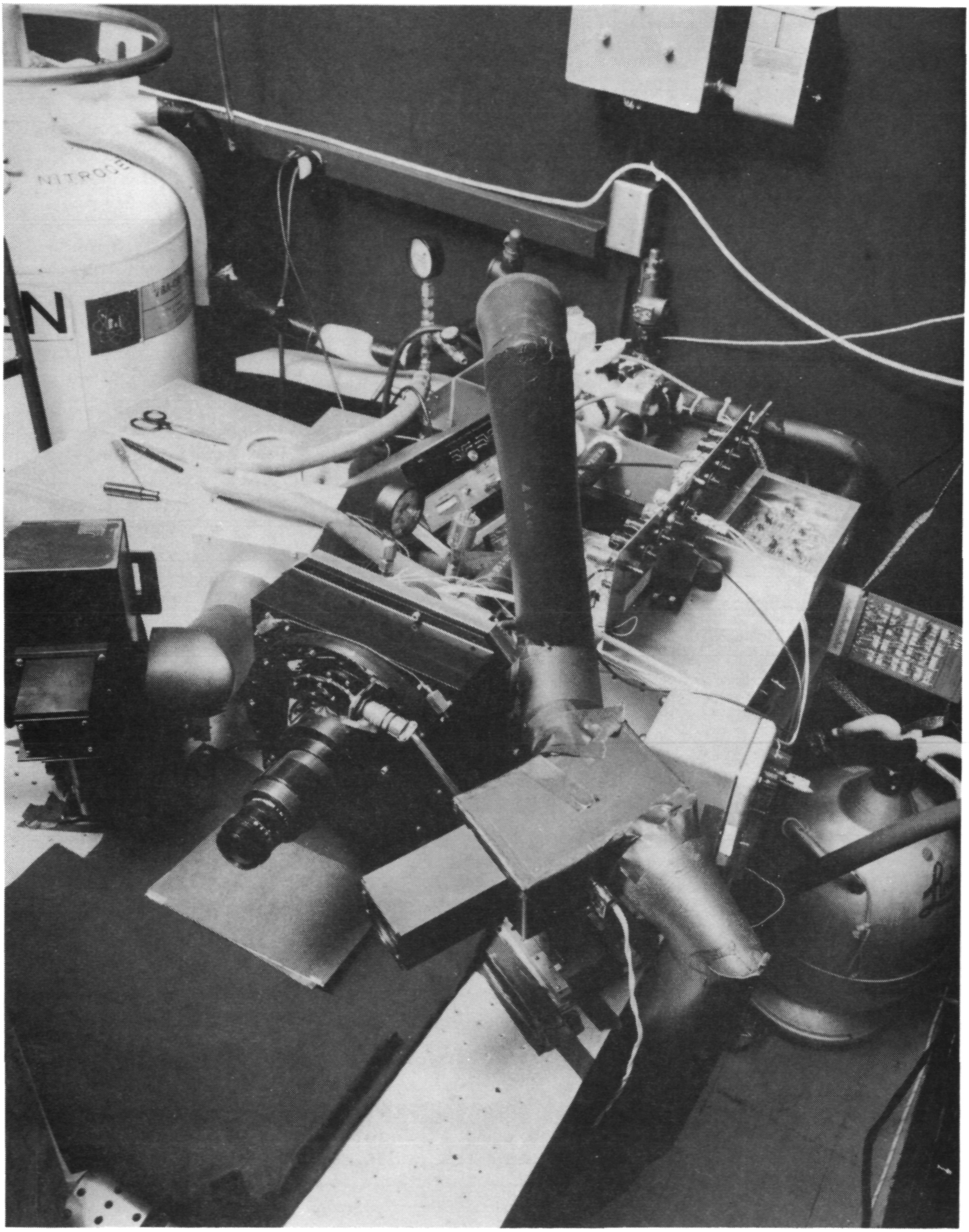


Figure 2-1. Lens, Camera Head, and Cooling Equipment for the JPL Sensor Test Set (JPL Photograph Negative No. 4126BC)

Figure 2-2. Display Monitors, Frame Buffer, and Computer for Sensor Test Set (JPL Photograph Negative No. 4131AC)

The purpose of the experimental electronic photography was to determine how such a document should be imaged and to create a data base of digital images to be used in the image-processing analysis. The experiments focused primarily on the definition of requirements for a system to accurately measure ink fading and flaking although images pertaining to other types of degradation were also acquired.

The CCD camera was used during these experiments because of its advantages relating to film and vidicons (TV tubes). Images from a CCD camera are produced in digital form and are immediately amenable to computer analysis, unlike film, which requires the costly intermediate step of scanning. The CCD has a relatively low noise level, which is highly desirable when making accurate photometric measurements. The CCD is far more light-sensitive than film or vidicons, which is desirable when photographing objects that should not be illuminated with strong light. An important feature in the CCD's photometric linearity: The signal out of the CCD is directly proportional to the amount of light impinging on the CCD. This linearity greatly simplifies the problem of calibrating the system for ink fading. Finally, unlike the vidicons, CCDs possess high geometrical fidelity. This means that images are recorded with no distortion of spatial relationships.

The CCD itself is a solid-state silicon chip, sized approximately 12 x 12 mm (Figure 2-3). The "virtual phase" CCD used consists of an array of 800 x 800 (640,000) tiny light-sensitive areas called pixels. Each pixel has its own slightly different sensitivity to light and must be individually calibrated. To reduce the random noise in the CCD to extremely low levels during long-duration exposures, the CCD cameras at JPL are cooled with liquid nitrogen to temperatures of below -70°C.

The Petition and Memorial of Freemen document, on its mount, was securely attached to the optical table with high quality optical bench posts and magnetic mounts. The CCD camera, lighting, electronics, mounted PMF, and optical table are shown in Figure 2-4. The imaging was performed with the PMF mounted vertically, illuminated by two light sources, one on each side of the camera lens.

3. Experiment Objectives

The objectives of the electronic imaging were as follows:

(1) To determine the effect of spatial resolution on reproductions of writing and parchment texture.

(2) To exploit the high signal-to-noise of the CCD imager for detecting subtle changes in a document.

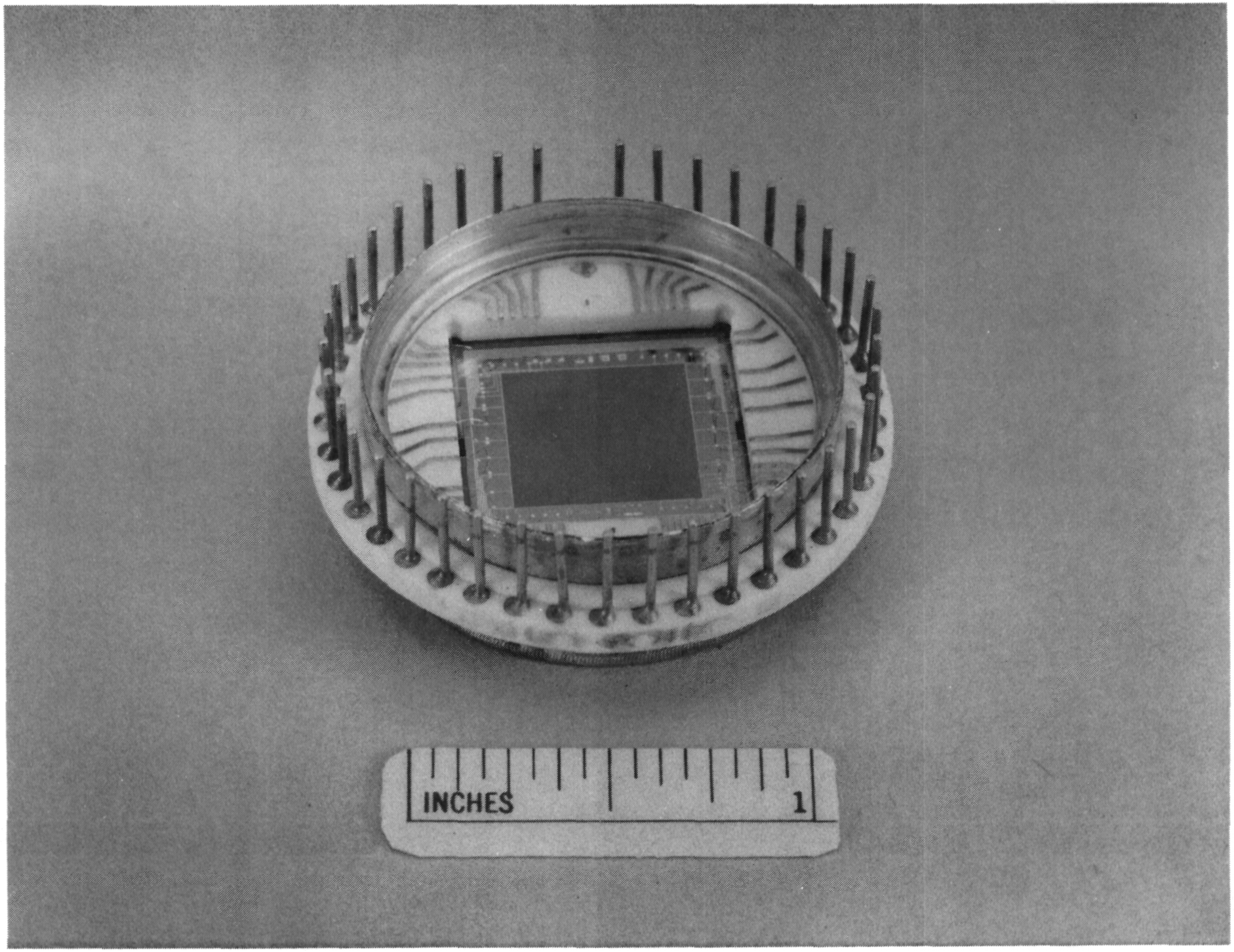


Figure 2-3. The 800 x 800-Element, Virtual-Phase CCD. The sensitive area of the detector is the square area inside the circular mount (JPL Photographic Negative No. 345-1653BC)

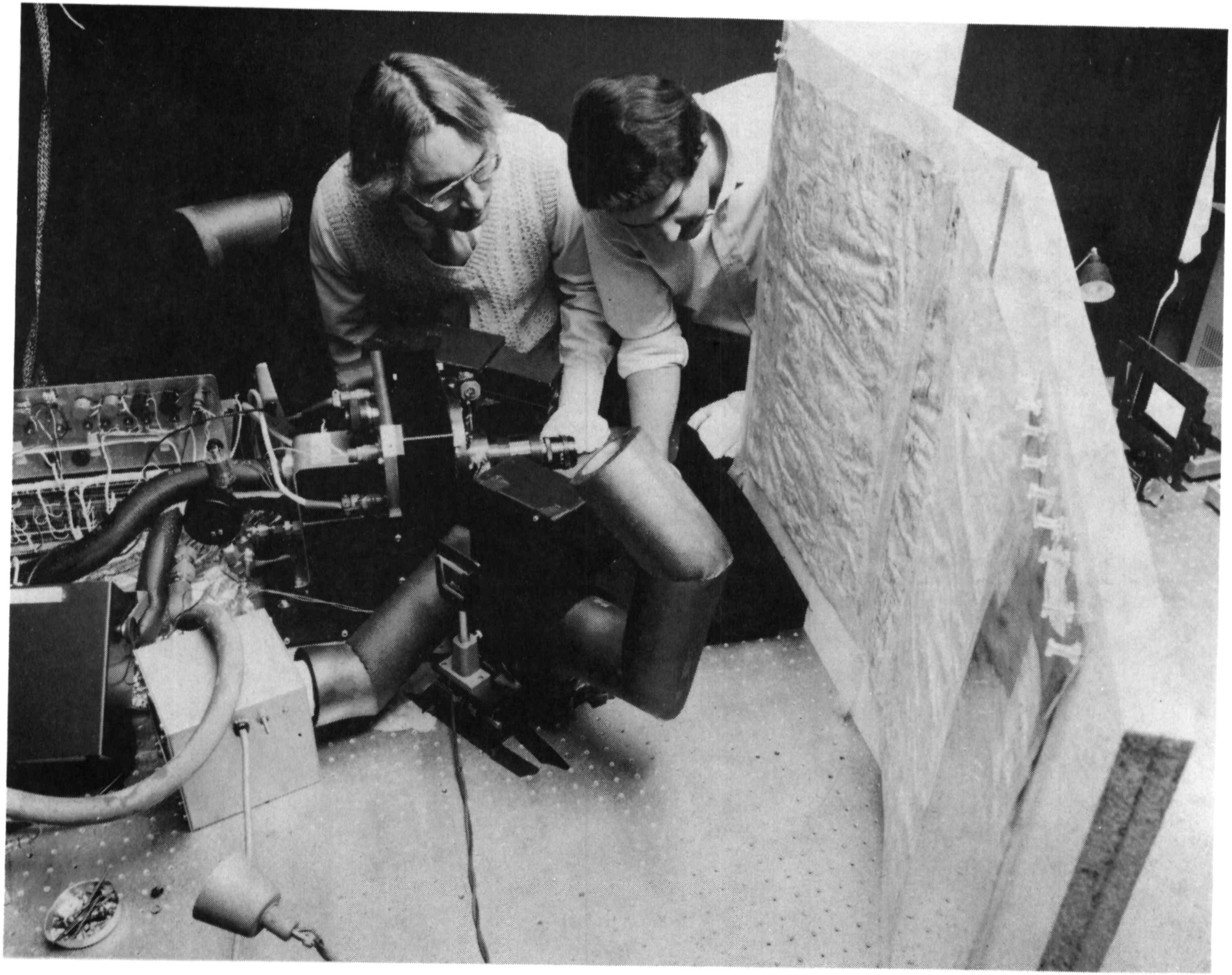


Figure 2-4. Petition and Memorial of Freemen (PMF) Document Mounted in Position for Imaging with the Sensor Test Set

(3) To explore the effect of different spectral bands on visibility of writing and textures.

(4) To evaluate methods of detecting change in writing or the condition of the parchment.

(5) To assess the value of raking incidence illumination for detecting changes in the relief of the parchment.

(6) To determine the feasibility of focusing on parchment texture.

4. Experiment Results

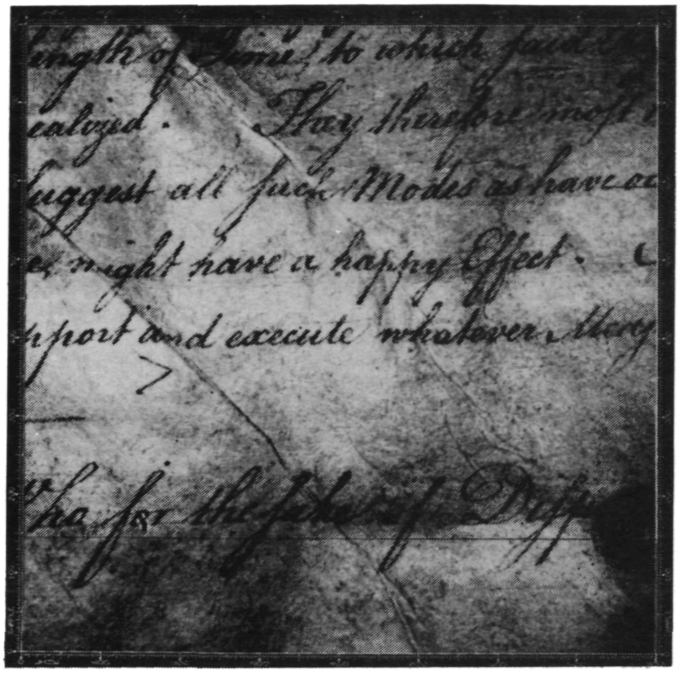
A total of 420 images were acquired of a test target used in setting up the optical system, the PMF document, the white reflective tile, contrast test targets, miscellaneous targets, and two light-response calibration sequences. The number of uniquely informative images were less because two to four images of the same scene were often acquired so that they could subsequently be averaged to increase the signal-to-noise ratio.

The most difficult part of this experiment was to align targets parallel to the focal plane and bring them into focus. Focusing was performed by moving the lens in its mount, acquiring an image and inspecting it. This was done on a trial-and-error basis. The suggested method for focusing in the system to be installed at NARS is described in Section VI. Focusing was more difficult at higher spatial resolutions because of the smaller depth of field.

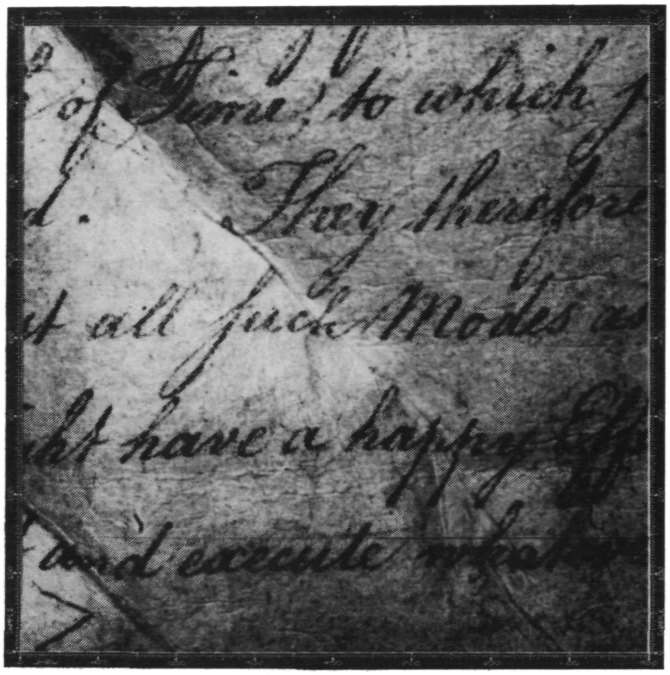
Owing to the geometrical restrictions of this particular CCD test set, the entire PMF document could not be accessed for imaging. Images were restricted to a 4-in.-wide strip along the two sides of the document. Nonetheless, a variety of useful images was acquired. After verification of quality, the images were written onto magnetic tape for transfer to the Image Processing Laboratory (IPL).

Some examples of the images acquired during the test appear in Figures 2-5 and 2-6. The initial digital analysis of these images at the IPL led to the following general results, which are relevant to a system to monitor the condition of the Charters of Freedom:

(1) It is feasible to use contrast as a measure of readability of penstrokes. In order to determine subtle changes in readability, very accurate contrast measurements are needed. This will demand careful experimental technique and fairly complex image processing.



a



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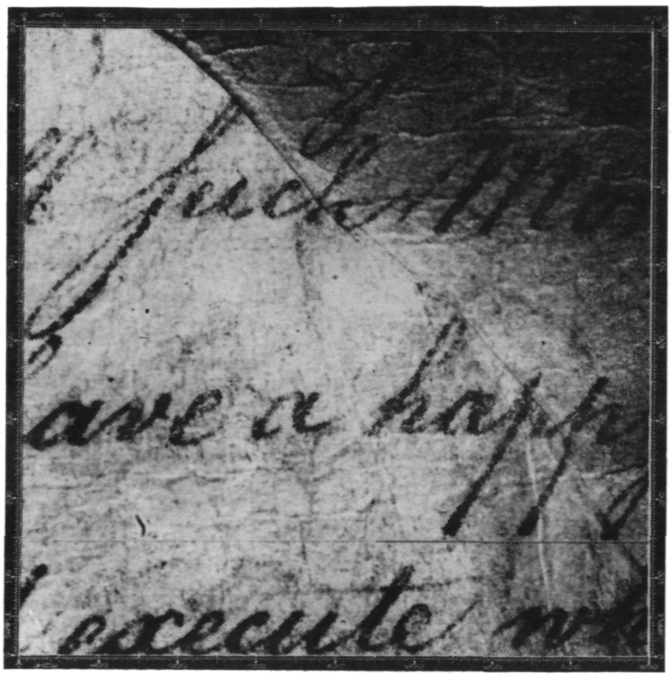
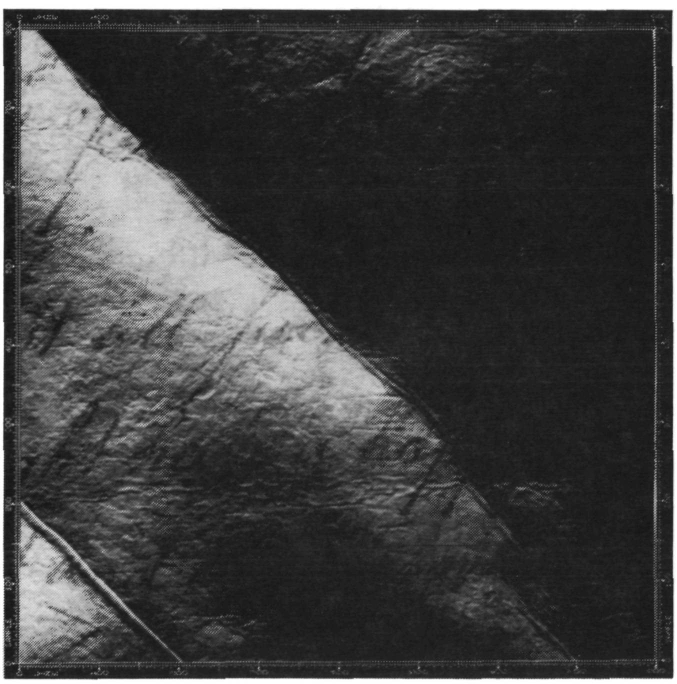


c

Figure 2-5. Segments of PMF Document Imaged with Diffuse Illumination (a) 300 Lines (b) 500 Lines (c) 800 Lines per Inch

a

b



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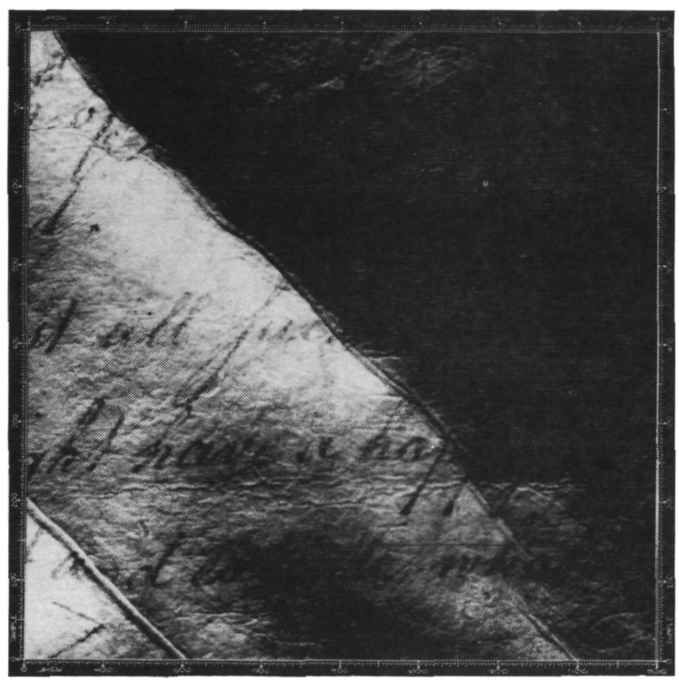

d

Figure 2-6. An Image of a Segment of the PMF Document Viewed Through (a) 5000-Å and (b) 8000-Å Narrow Pass Filters. Contrast is much Lower in (b). Another Segment of the PMF Document (The Same One Imaged in Figure 2-5(a) is Viewed with Raking Incidence Illumination of (c) 10° and (d) 20° from the Plane of the Parchment.

(2) Ink-to-parchment contrast is a function of the wavelength of illumination. The Charters should be examined at five wavelengths. Five wavelengths in the range of 0.5 to 1 μm are desirable; three would be acceptable.

(3) A spatial resolution of 800 lines/in. is adequate to the monitoring task. It provides typically 6 to 10 pixels across the width of all but the finest penstrokes in the PMF. It resolves, or brings into more detailed focus, parchment texture that is to be used for automatic focusing. It exceeds the resolution (300 lines/in.) of the human eye. A resolution greater than 800 lines/in. could be used for the Charters because the glass in contact with the documents should help suppress the undulations in the parchment and allow the full field of view to remain in focus at smaller depths of field.

(4) The system should include a method for rapidly and reliably focusing the camera. The camera should be focused on the fine-scale texture of the parchment enhanced by raking incident illumination prior to performing photometric measurements with diffuse illumination.

(5) To exploit the full dynamic range of the sensor, exposure times should be chosen that yield a signal near the highest recordable signal that lies on the linear portion of the sensor transfer curve (see Appendix B, Figure B-1).

Subsequently, a more detailed analysis of these data was directed towards the development of a technique for accurately and reproducibly measuring the contrast of pen strokes. The methods explored, which are described in more detail in Appendix 2, were:

(1) Histogram moments with no segmentation.

(2) Intensity segmentation of histogram into ink and parchment, followed by contrast measurement.

(3) Spatial segmentation of the image, followed by contrast measurement.

A description and an assessment of the comparative merits of these techniques is given in Table 2-1. It was concluded that some variant of the third technique involving spatial segmentation was necessary to achieve measurements of sufficient accuracy

Table 2-1. Comparison of Alternative Digital Image-Processing Methods for Measuring Deterioration in Readability

Method	Concept	Evaluation: Advantages	Evaluation: Disadvantages
1. No Segmentation/ Histogram Moments	Determine the histogram of an area of parchment and penstrokes Compute mean and higher order moments of the data Repeat measurement Compare histograms (subtraction) Compare means and shape measures	Simplest method	No clearcut definition of contrast No insight into what is happening to ink and parchment
2. Intensity Segmentation/ Contrast Measurement	Calculate the histograms of intensity values for two adjoining areas Parchment only without penstrokes Parchment marked with penstrokes Fit the parchment-only data with Gaussian curve; determine mean and variance Perform a best fit of this Gaussian curve with the histogram of parchment marked with penstrokes Subtract the two curves to determine the brightness of penstrokes Calculate contrast of parchment and penstrokes Repeat for subsequent observations of same area	Simple method Fairly insensitive to registration errors Potential for further improvement using multispectral segmentation	Measurements of contrast probably no better than 10% Will not work well on low-contrast letters

Table 2-1. (Cont'd.)

Method	Concept	Evaluation	
		Advantages	Disadvantages
3. Spatial[a] Segmentation/ Contrast Measurement	<u>Segmentation</u> Discriminate ink from parchment on the basis of measurements of intensity and spatial context Current implementation uses: A measure of texture (autocorrelation function) An autoregressive model of individual brightness values A Bayesian scheme for classifying pixels and blocks of pixels to form templates defining penstrokes and parchment <u>Contrast Measurement</u> Calculate contrast of parchment and penstrokes <u>Measurement of Change and Trends</u> Register new image with old Repeat contrast measurement using old template	Most accurate method Can also be used to characterize textural changes and ink removal	Requires sophisticated software

[a]The line-segmentation technique described in Appendix B is not described in this table.

to provide an early indication of change in the Charters of Freedom (see Section III). Further work is needed to determine how accurate those measurements can be.

F. OPTICAL PROPERTIES OF THE ENCAPSULATING CASE

A section of a glass case identical to those used for encapsulating the Charters of Freedom was tested for optical characteristics relevent to imaging enclosed documents.

Spectral reflectance and transmission measurements performed on the glass revealed no anomalous absorption in the spectral range of interest, 0.4 to 1.1 μm. However, no absolute measurements of reflectance and transmission of the bulky samples could be obtained because of the size restrictions of instruments suitable for absolute measurement.

The primary concern in imaging the document was multiple reflection and scattering at the surfaces of the two glass plates that lie between a document and the imaging scanner. Initial work was directed toward an understanding of where these reflections occurred and whether they could be mitigated with polarized light. The possibility of reducing the scattered light effects with innovative scanning techniques was also examined. The setup for examining these reflections with a laser (chosen because it provided a narrow pencil beam with sufficient brightness to produce easily discernible reflections for glass surfaces) is shown in Figure 2-7.

Actual images of a document viewed through the two layers of glass were also obtained. To provide maximum flexibility in the kinds of lighting that could be used, these data were acquired with photographic film and not an electronic imaging device. The present STS camera system would have been cumbersome to use for this series of tests. The test setup for imaging a document with diffuse illumination is shown in Figure 2-8.

The resulting image (Figure 2-9) shows a number of significant effects caused by the glass:

(1) A loss of contrast of pen strokes for areas behind the glass relative to areas with no glass cover.

(2) A loss of contrast of texture and undulations for the same reasons.

(3) A reflection showing the camera structure or a shadow of the camera in the lower middle of the image.

The most serious effect in this image is the reflection of the camera. By tilting and displacing the camera slightly, it is

possible to move it out of the field of view (Figure 2-10), thus removing the reflection.

Finally, in Figure 2-11 the appearance of document under raking incidence lighting is shown. Under these conditions a conspicuous drop in the brightness of the parchment under the glass relative to uncovered parchment can be seen. Reductions in contrast also occur. Comparison of this image with the image in Figure 2-10 illustrates the effectiveness of the diffuse illumination in suppressing contrast effects due to the parchment.

These imaging tests are not directly applicable to all methods of electronic scanning of the document, but they illustrate some of the potential problems of reflection and contrast reduction and some of the ameliorating measures. If an electronic framing camera like the STS camera were used in the NARS system, reflection problems like those in Figure 2-9 would occur. However, because the depth of focus of this camera is much shorter, they would not be as noticeable. It might be quite difficult to rotate these cameras out of the field of view while still maintaining good focus.

If, on the other hand, a line-scan were used (see Section V), the camera reflection would appear identically on all scan lines and possibly could be compensated for. This issue will be examined more fully in the detailed design phase.

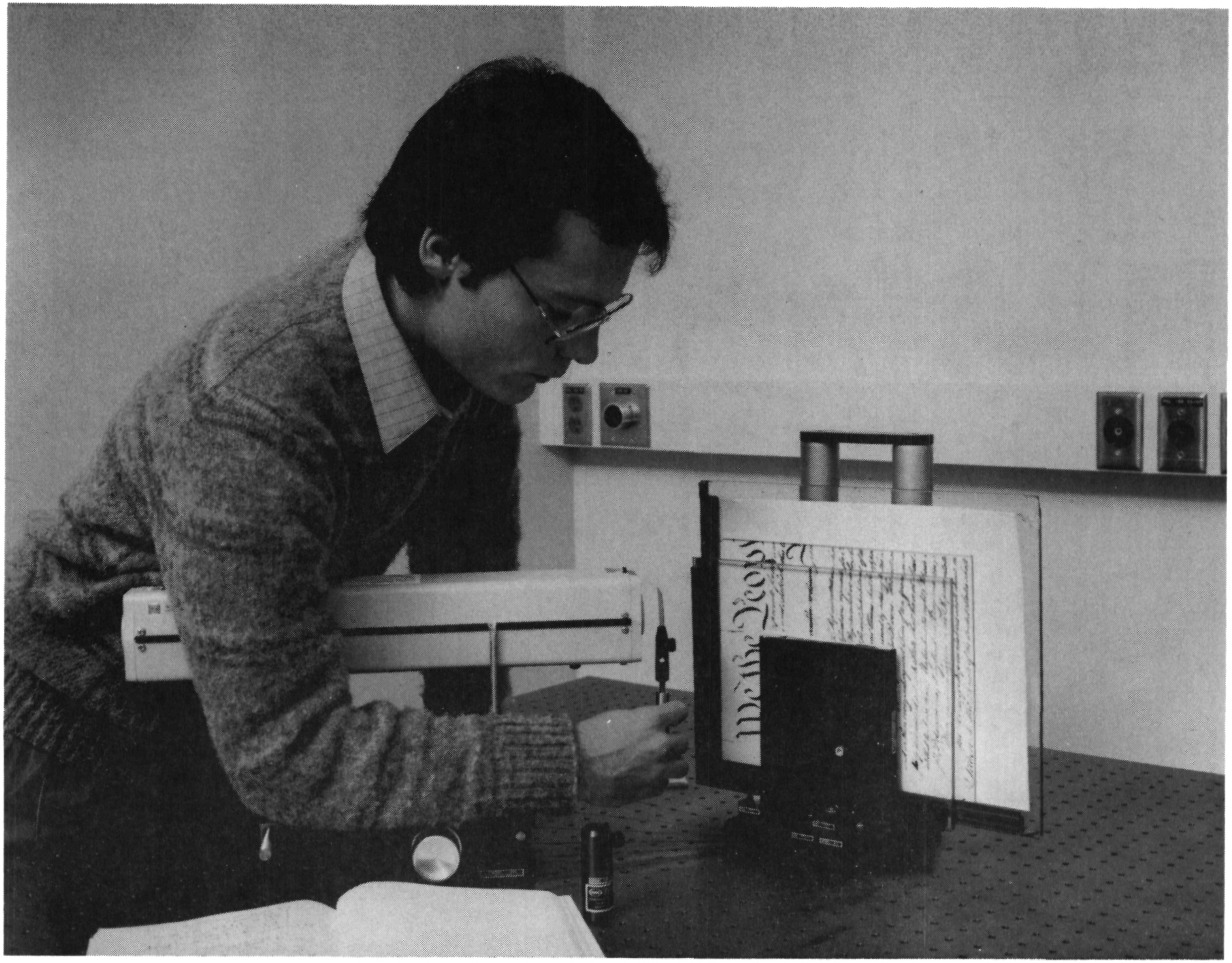

Figure 2-7. Test Setup for Studies of Reflections and Scattering from a Prototype of the Glass in which the Charters of Freedom are Mounted (JPL Photograph Negative No. M-4155BC)

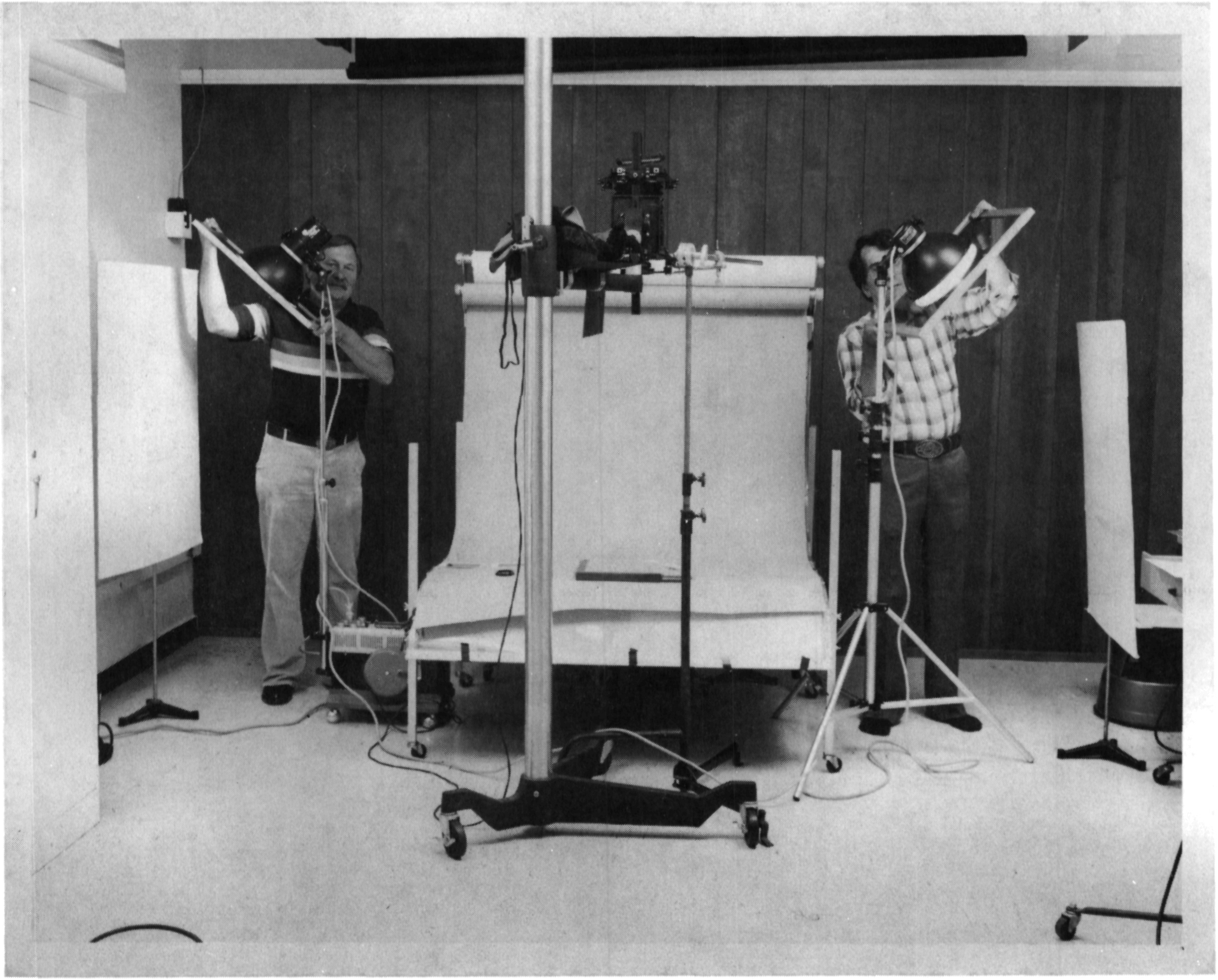

Figure 2-8. Test Setup for Photography of a Test Document Inside Sample Glass Case (JPL Photograph Negative No. 4187-BC)

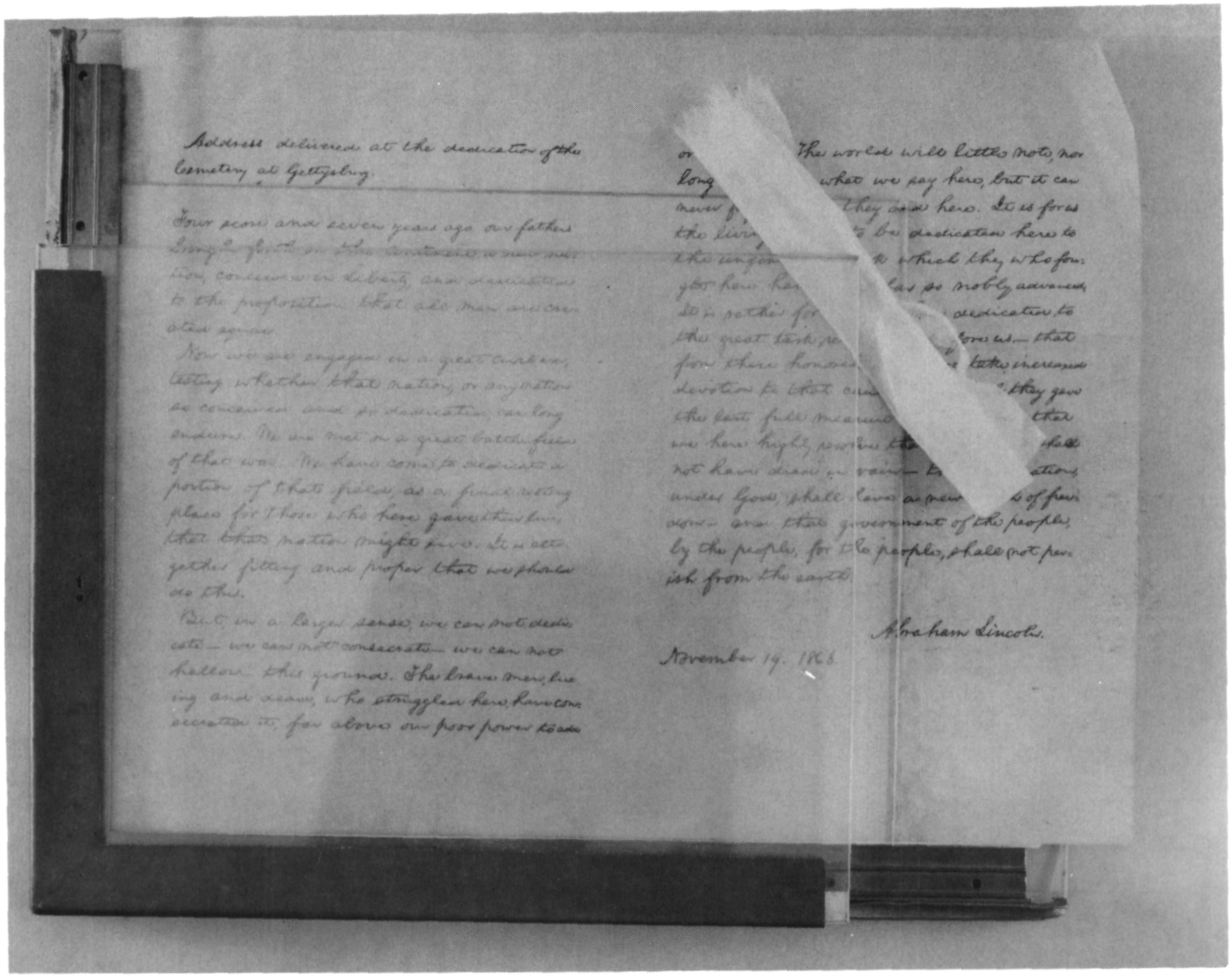

Figure 2-9. Image of Test Document Viewed Through Glass Case with Diffuse Illumination. Note reflection of camera (JPL Photograph Negative No. M-4184A)

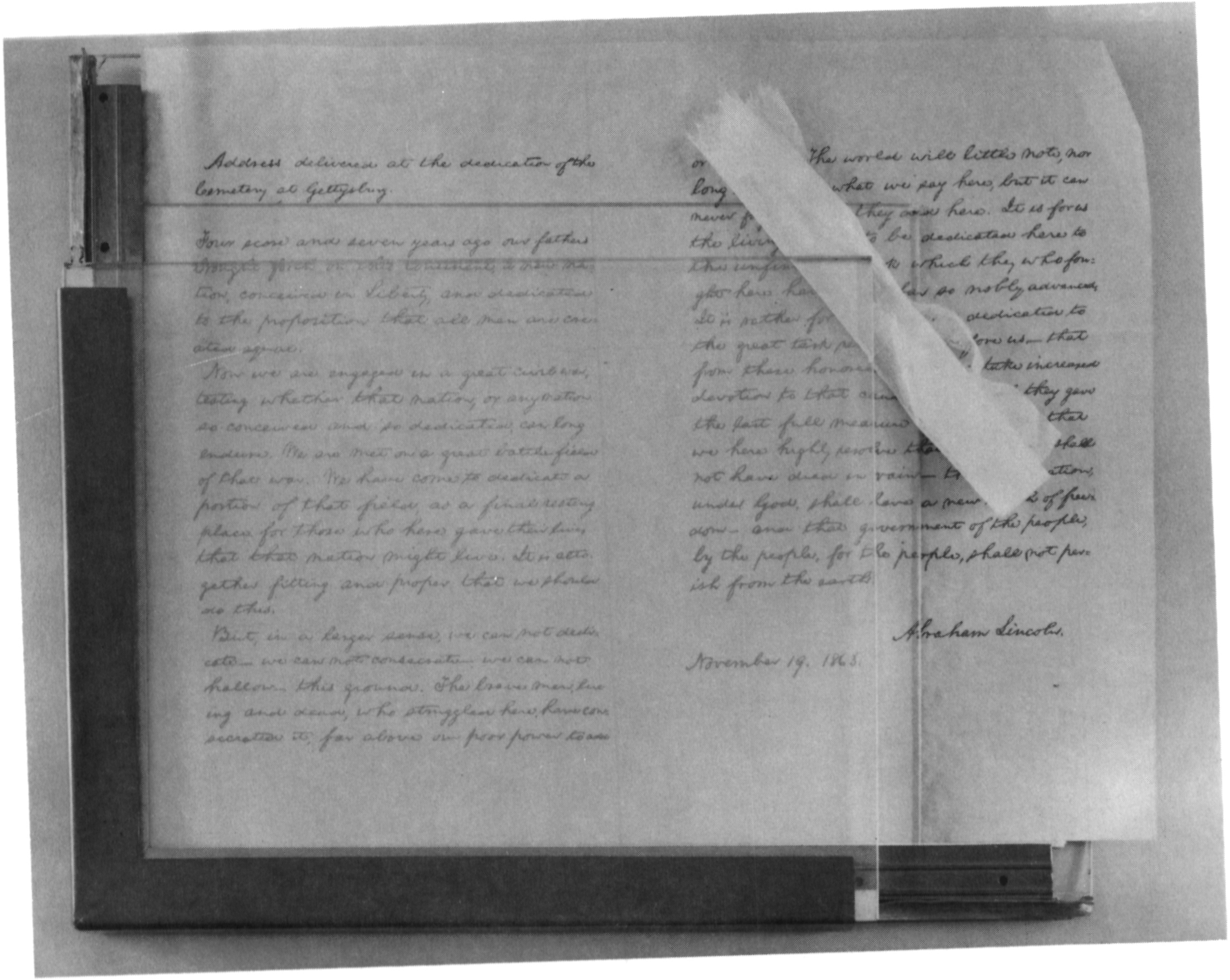

Figure 2-10. Image of Test Document Viewed Through Glass Case with Diffuse Illumination. Camera was moved to remove reflection (JPL Photograph Negative No. M-4185A)

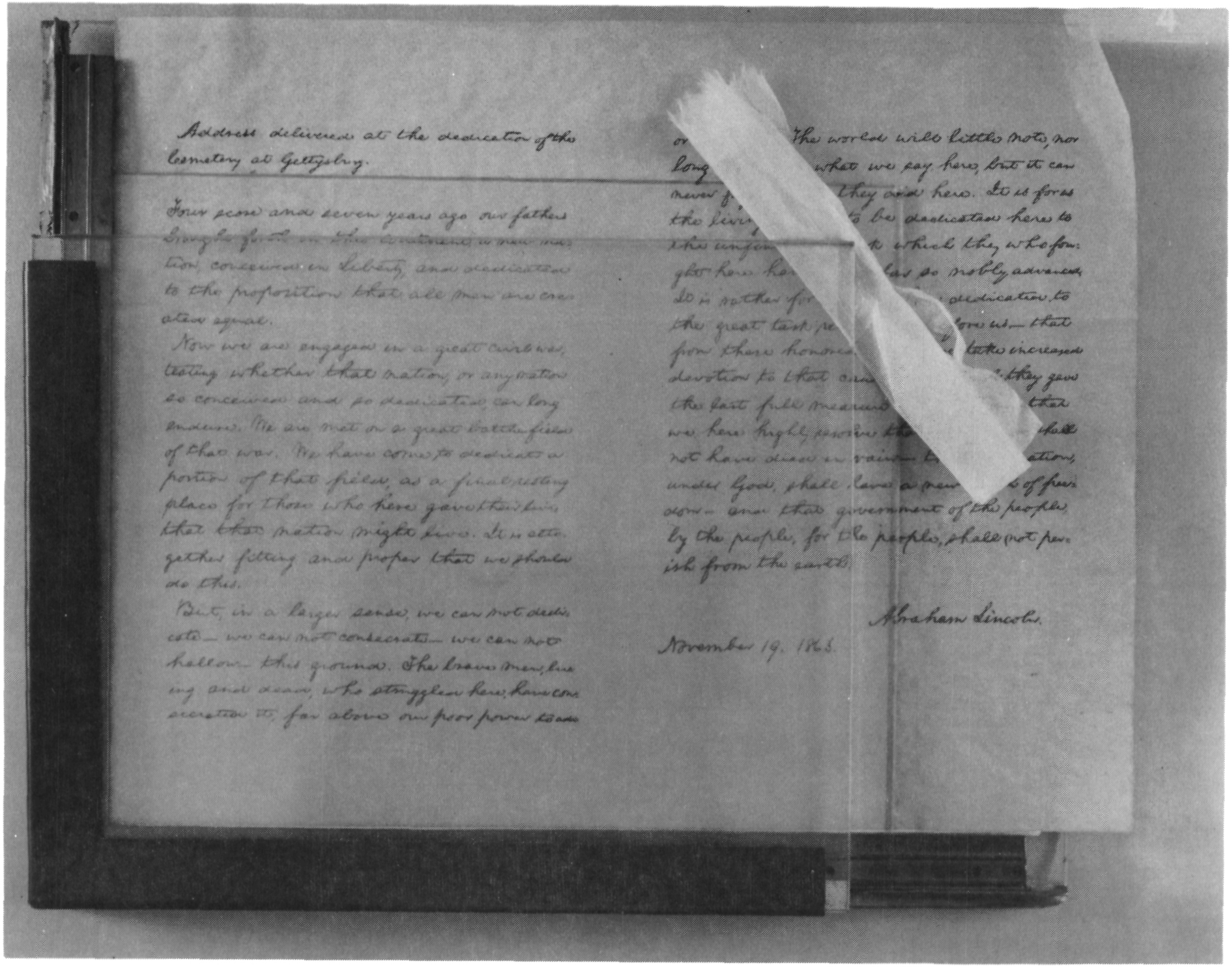

Figure 2-11. Image of Test Document Through Glass Case with Raking Incidence Illumination (JPL Photograph Negative No. M-4184B)

SECTION 3

ANALYSIS SYSTEM REQUIREMENTS

The objective of the electronic imaging and analysis system described in this document is to monitor the state of preservation of the Charters of Freedom (References 3-1 and 3-2). However, it was felt that to carry out that experimental objective effectively, it would be valuable to use this system in other scientific tasks at the Archives. Accordingly, JPL was requested to identify other objectives for such a system and to determine the possible impact on system design (Reference 3-3).

A. REQUIREMENTS FOR MONITORING CHARTERS OF FREEDOM

1. General Requirements

The general objective of the monitoring system is to perform periodic inspections of the Charters of Freedom to detect evidence of change in these documents, specifically indications of progressive alteration of either the parchment or ink strokes. A confirmed deterioration in the readability of the documents was viewed to be a primary concern.

Deterioration in the readability of the documents could arise from the vibration associated with placing the documents on display each day and then restoring them to safe storage. This operation is implemented with a mechanical jack. Less likely is the possibility of damage from exposure to the very low light levels present in the case. Finally, there was concern about low-rate inorganic and organic processes of presently unknown nature that might be affecting these documents.

The primary goal of the monitoring system was to detect evidence of deterioration but not necessarily to specify its cause (Table 3-1). Because gradual deterioration activity over many years would result in a cumulative effect on readability, it was necessary to detect these changes before they became visible to the unaided eye. Hence, a quantitative approach involving scientific imaging, coupled with a carefully designed experimental method, was needed. By performing high-accuracy measurements of readability, the progressive changes in contrast could be detected long before they resulted in an unreadable document (Figure 3-1).

Table 3-1. Measurement Objectives

Objective	Aging Mechanisms
Monitor factors that could affect ability to read Charters of Freedom with unaided eye	Ink Grain Fading Ink Fading Parchment Fading/Staining Parchment Decomposition Foreign Matter in Display Case

In the experimental measurements program it was discovered that contrast can be determined from the digital analysis of penstrokes and that this contrast measurement is an appropriate measure of readability. Accordingly, a set of requirements was defined for the NARS monitoring system. These include contrast and several other observables that can be measured and that may affect document deterioration (Table 3-2).

2. Specific Requirements

The system functional requirements for monitoring the Charters of Freedom were defined from experimental measurements (Table 3-3). These requirements were reviewed with NARS personnel to ensure that the necessary conservation requirements were incorporated. An explanation of the drivers for these functional requirements follows.

The <u>best resolution</u> of at least 800 pixels per inch was based on experimental measurements after review with NARS personnel. The requirement for <u>coverage</u> of at least one inch square at this best resolution derives from the judgment that images

Table 3-2. Properties of Document Accessible for Measurement

1. Average Spectral Reflective of Pen Stroke
2. Average Spectral Reflectivity of Parchment
3. Area of Pen Stroke
4. Texture of Pen Stroke
5. Texture of Parchment
6. Flaking of Individual Ink Grains
7. Appearance of Foreign Matter
8. Dimensional Ratio
9. Contrast Ratio
10. Color Ratio

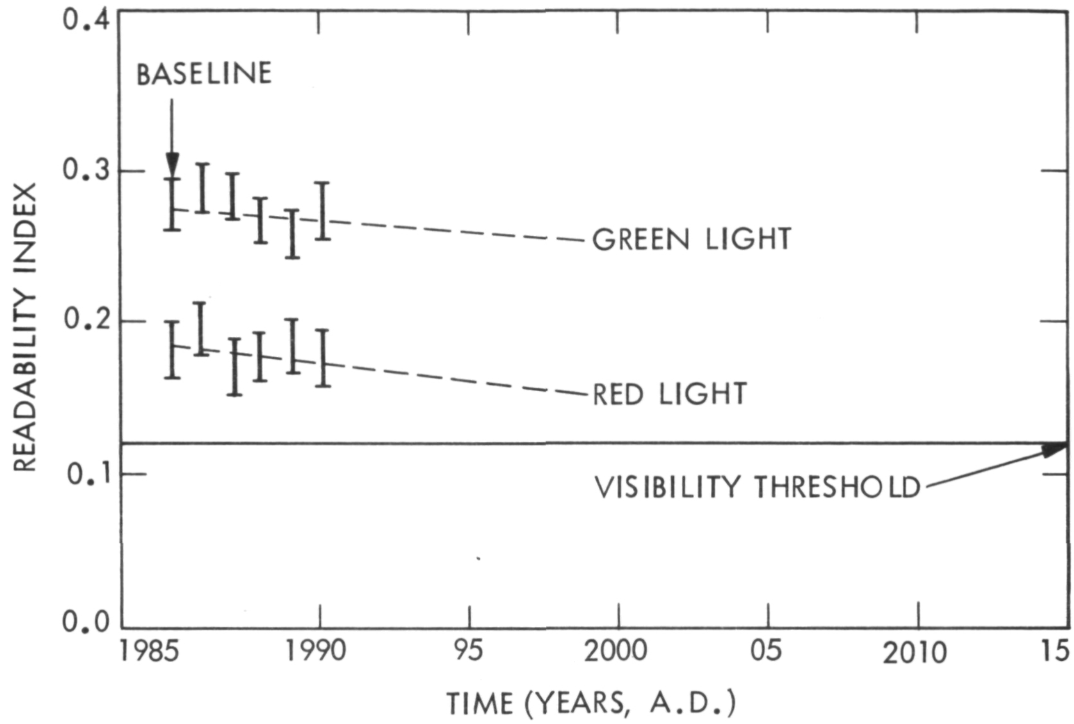

Figure 3-1. Measurement of Penstroke Fading

smaller than this contain too limited an area for useful analyses. Digital mosaicking of smaller images together to form images on one inch size or larger was viewed to be a costly and hence an unacceptable alternative.

The spectral range of 500 to 1000 nm is primarily dictated by two measurement constraints. Observations below 500 nm are precluded by the absorption of the glass in the encapsulating case. The upper limit of 1000 nm is set by the response curve for silicon electronic sensors. which cuts off sharply at longer wavelengths than 1000 nm. The resulting bandpass is adequate to provide measurements of the visual appearance of the documents and potential important information on the near-infrared characteristics. Five spectral bands are desirable for this procedure, but three should be adequate.

The brightness ratio of parchment and ink as viewed through the encapsulating case is estimated to be less than 2:1. Consequently. an extended dynamic range is not mandatory. However, a signal-to-noise of at least 100:1 referred to in a single pixel is desired, and this is realizable with the read noise of 100 electrons and saturation signal of 50,000 electrons specified in Table 3-3.

Table 3-3. Functional Requirements

Functions	Requirements
Best Resolution	800 pixels/in.
Coverage	1-in. square at best resolution
Spectral Range	500 to 1000 nm
Spectral Bands	5 bands 100 nm full width Center wavelength stability ± 1 nm
Dynamic Range	Read noise 100 electrons RMS Saturation 50000 electrons
Photometric Stability	Calibratable to ± 4% RMS reflectance per pixel
Linearity	± 2% RMS over dynamic range
Geometric Distortion	± 1 pixel per frame runout
Magnification	Controlled to ± 0.1% Constant to ± 0.001% over spectral range
Focus	Controlled to 1/4 depth of focus
Glare	Provisions for rejecting reflected and scattered light from a glass encapsulating case
Alignment	Translation ± 1 pixel Rotation ± 1 pixel per frame runout
Blemishes	Minimum - Protect from dust
Lights	Precision control of illumination angles
Computer	Proven hardware Required memory and peripherals Minimize new software development Maintenance by manufacturer

Table 3-3. (Cont'd.)

Functions	Requirements
Software	Maximum transfer existing programs Executive and utility Calibration/decalibration Applications Archival log and storage
System	Self-contained deliverable User-friendly Minimum maintenance Document safety No cryogenic cooling

Photometric stability is a critical requirement for this experiment. Absolute and relative stability are usually considered separately. Measurements of the relative brightness of ink and parchment suffice to characterize any change in the contrast and readability of the documents. Measurements of absolute brightness and reflectivity could contribute additional information on the mechanism of deterioration. The linearity requirement is closely tied to the generation of photometrically useful data.

Geometric distortion and magnification stability and alignment are important to the successful registration of images obtained in different spectral bands or at different times. Focus is also important if registered images are not to be degraded, and focal stability is needed for obtaining images under strictly comparable conditions.

The glare requirement is one of the most critical. No numerical requirement has been defined, but the goal is to achieve high accuracy measurements of contrast through the glass case.

A summary of the general hardware and software requirements for the image analysis system is given in Table 3-3. No firm requirements have yet been developed about where that system should be located (at JPL or NARS) or how many individual document areas it should be capable of analyzing. In fact, several image-analysis options have been examined and their capabilities outlined in Section VI.

To make an informed judgment on requirements for equipment location and processing values, NARS should be familiar with the state-of-the-art capabilities as described in Section VI.

The processing flow envisaged for acquisition and analysis of the data is described in Table 3-4. Terminology used is defined in the Glossary.

B. OTHER PRESERVATION AND VALIDATION REQUIREMENTS

Originally, JPL was requested to design a system for NARS specifically to monitor the condition of the Charters of Freedom. Later an additional request (Reference 3-3) was made that the system include a general research capability and specifically that the system should be flexible enough to allow the National Archives to conduct image analyses on various documents in addition to the Charters. The minimum would be the application of the same protocols used to monitor the Charters on unencased documents. Some on-site interactive computing would be desirable.

This capability would be used by research personnel from other museums and institutions, as well as by NARS. A preliminary survey of museum and library personnel indicated interest in the following general areas:

(1) Conservation and preservation.

(2) Recovery of lost text.

(3) Authentication of art objects and documents.

The conservation issues include air-pollution damage to books, leather, rot, changes in the crackle pattern of old paintings, dendrochronology, mold growth, and microscopic fiber cracking. The text recovery issues include reading faded parts of the Dead Sea Scrolls as well as other documents.

This research capability would have an impact on the NARS system hardware and software. A general, flexible image-processing software environment is required, in addition to the more structured, fixed, procedurized software that would be employed for the Charters' analysis. The latter will ensure that the Charters' data reduction procedure can be duplicated exactly over the years. The former will allow the system to be used for creative research as well.

Table 3-4. Processing Flow

Calibrate camera for spectral sensitivity
Precision align and focus camera
Image-selected area of document
Decalibrate image : photometric and geometric
Observables[a]
Intensity: 1, 2, 9, 10
Multispectral: 1, 2, 9, 10
Spatial: 1, 2, 3, 4, 5, 9, 10
None: 6, 7, 8
Display enhancement: stretch/zoom/false color
Data logging and storage

[a] The numbers listed here refer to the observables listed in Table 3-2.

The additional hardware features that would be useful include:

(1) A light table for imaging translucent and transparent targets for digitization of negatives and for imaging text under transmitted light.

(2) Repeatable raking light source.

(3) Selectable field of view.

(4) Adjustable distance from object to lens to enable the system to image pages of a book, for example.

(5) Narrowband ultraviolet source.

(6) Near infrared imaging.

(7) Thermal infrared imaging.

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SECTION IV

CONCEPTUAL DESIGN OF MONITORING SYSTEM

In this section a conceptual design of the monitoring system for the Charters of Freedom is described. Specific design issues associated with the two major subsystems of the monitoring system are covered in Sections V and VI. Photographic measurements (see Section III) are not discussed in this document but are treated in the implementation plan.

A. CONCEPTUAL DESIGN APPROACH

The monitoring system acquires electronic images of each document and performs an accurate photometric calibration. It may also include a capability for comparison of newly acquired images with images acquired in a previous monitoring session.

Block diagrams of two possible configurations are shown in Figures 4-1 and 4-2. The first system only acquires images. These images must be sent to JPL or another organization with digital image-processing capabilities for calibration and comparison. The second system (Figure 4-2) will also compare images and provides all the functions needed to determine if documents are deteriorating. As drawn in Figures 4-1 and 4-2, the two systems have identical configurations for the electronic camera and accessories. Specific details of the electronic camera and its accessories are discussed in Section V.

A drawing of the monitoring system installed at the Archives appears in Figure 4-3. At this level of detail the aforementioned design alternatives would only have a minor influence on the design of the electronic camera and its accessories. If the image-analysis system were located at NARS, then an additional rack of computer equipment would be included in the drawing.

B. ELECTRONIC CAMERA AND ACCESSORIES

1. Camera Mount

The camera mount is the major piece of equipment located in the alcove shown in Figure 4-3. It supports the electronic camera and other pieces of equipment related to imaging.

Its functions are to support, align, and focus the camera head and lens and to translate the camera relative to the document. It incorporates an X-drive to move the document, a Y-drive to move the camera head, and a Z-drive to focus the camera head. A preliminary design of the camera mount appears in Figure 4-4.

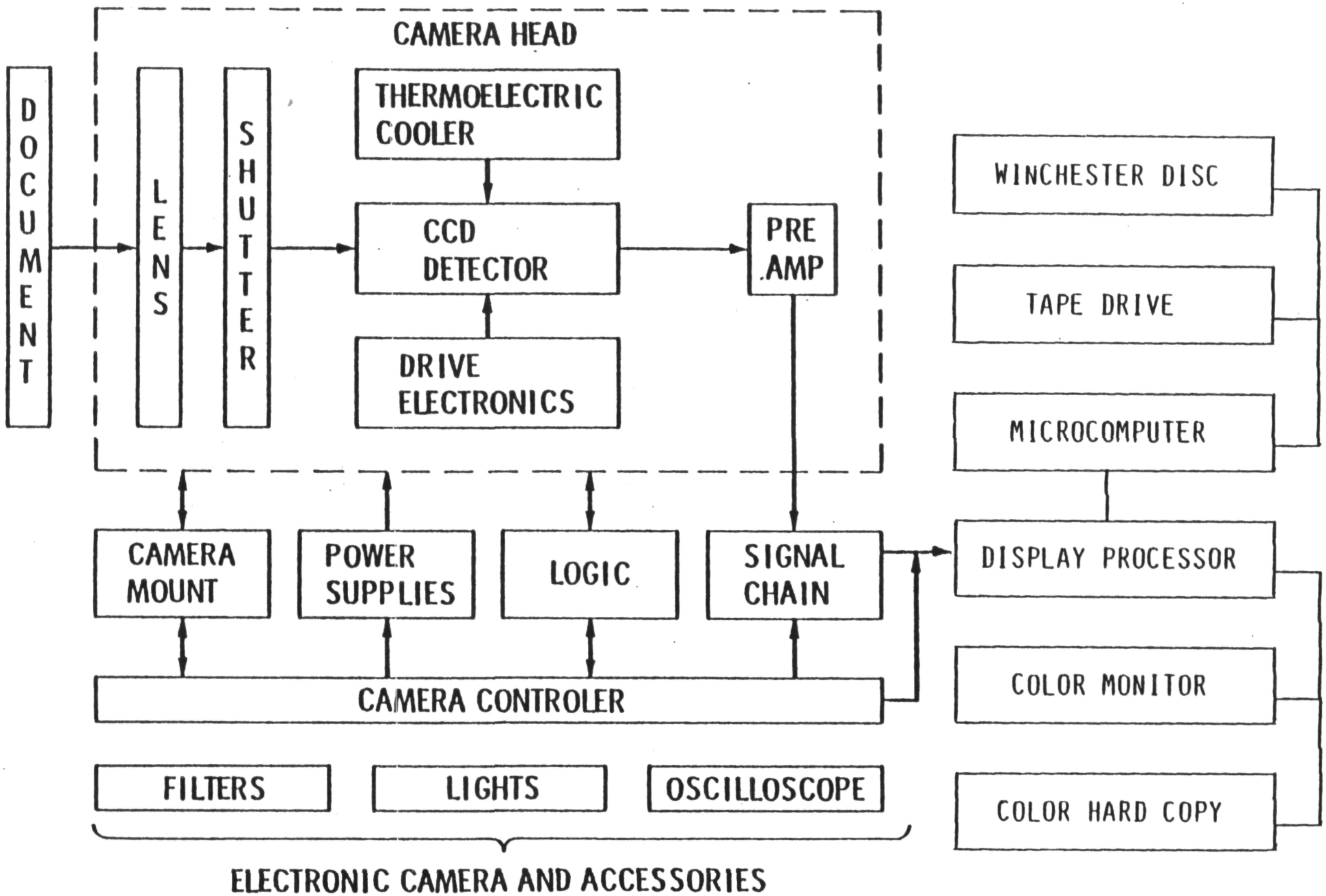

Figure 4-1. Functional Block Diagram of a Monitoring System for the Charters of Freedom. This design provides a capability for acquisition and display of images but not analysis

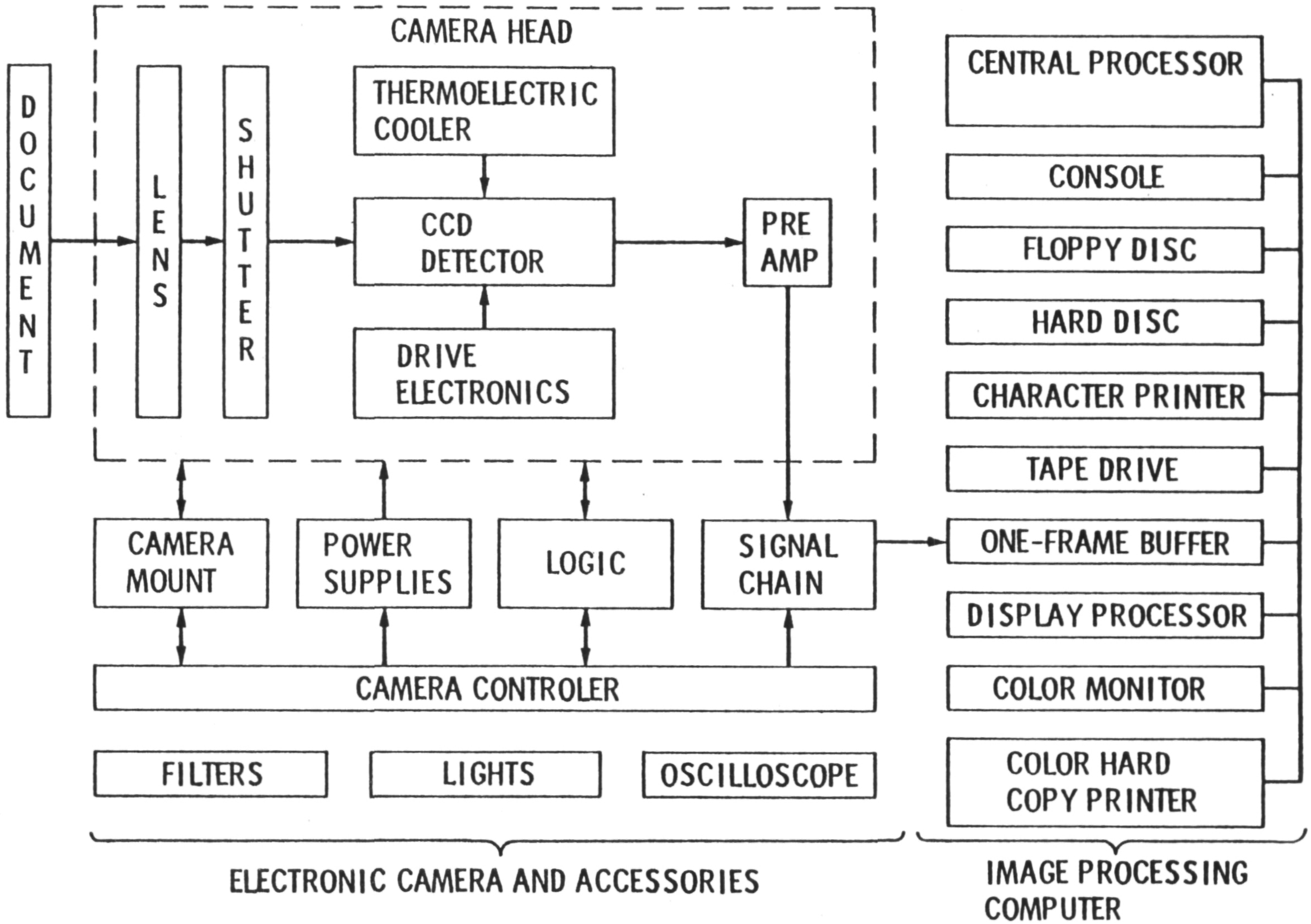

Figure 4-2. Functional Block Diagram of a Monitoring System for the Charters of Freedom with the Capability of On-site Analysis. Note that the image acquisition section (electronic camera and accessories) is identical to that shown in Figure 4-1

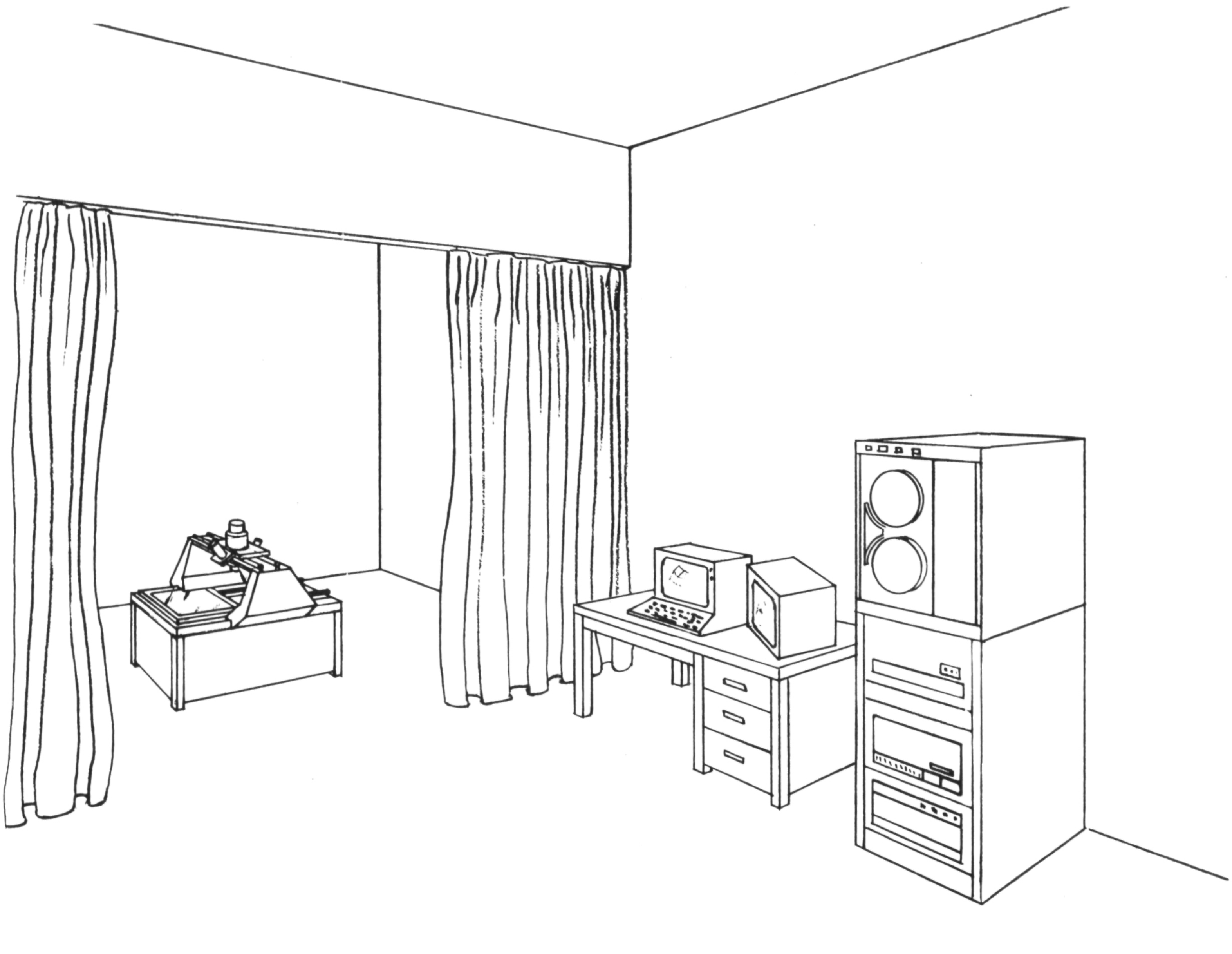

Figure 4-3. Installed Monitoring System at the National Archives

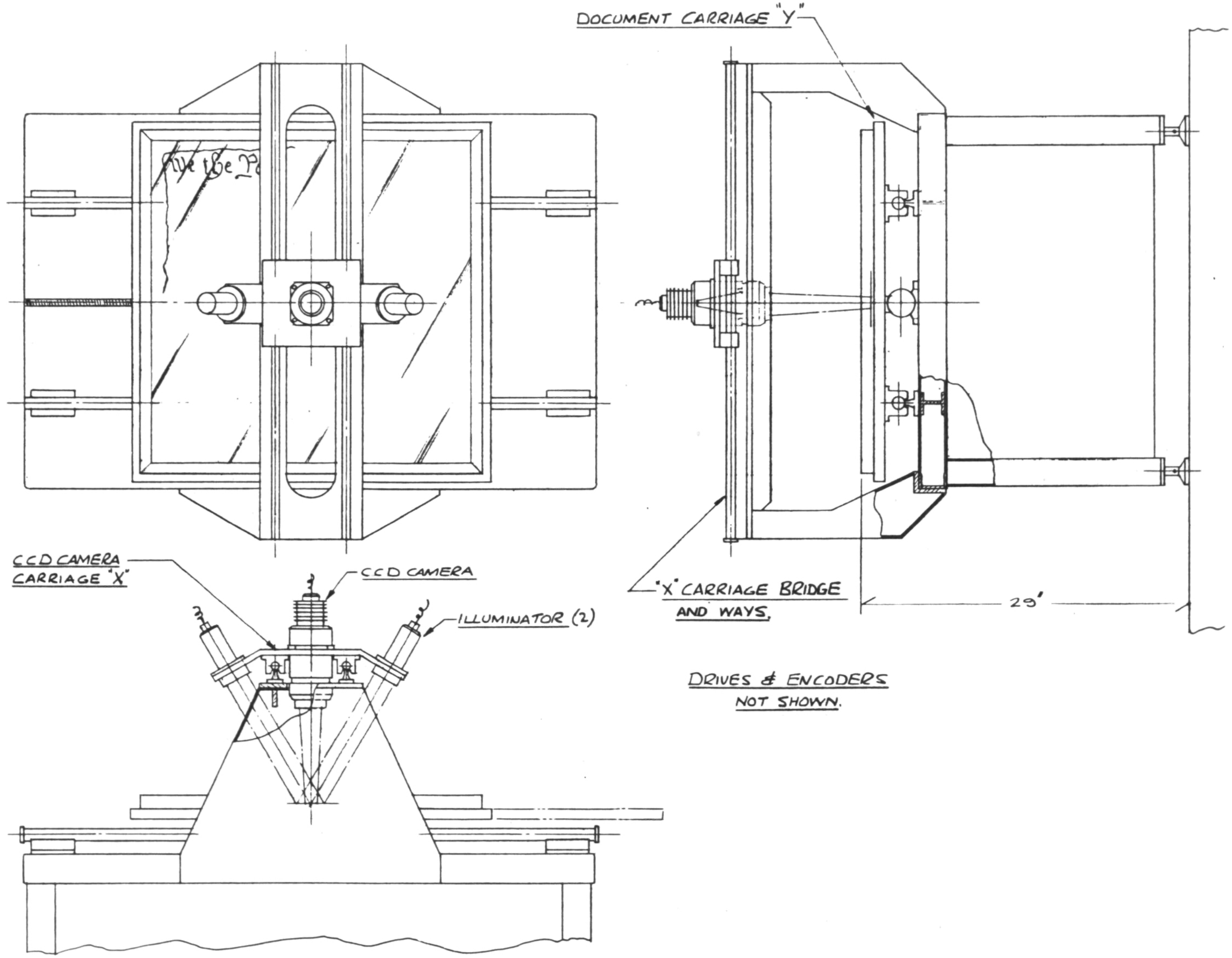

Figure 4-4. Preliminary Camera Mount Design

Open-loop optical encoders are used to register positional information. Positions must be referenced to fiducial markings on the document case or to prominent features on the document. There is no provision for rotating the camera head. Lamps and filters are carried on the camera head so that the illumination conditions are as identical as possible for all positions of the camera head.

Document safety is an important consideration. Both vertical and horizontal orientations of the document case were originally considered. The horizontal position is preferred for simplicity of design of the camera mount but requires safety precautions to avoid dropping heavy objects directly onto the case.

The detailed design of the camera mount is affected by the type of imaging technique that is used. Both area-array and line-scanner approaches have been considered and are reviewed in detail in Section V.

2. Lens

Satisfactory image quality can be achieved with a superachromat process lens. Although not optimized for infrared photography, it will provide adequate resolution between 700 and 1100 nm wavelength.

Scale reductions of approximately 2 to 10 will provide the broad coverage needed initially to locate an area in the image and the higher resolution view of a 1 x 1-in. segment of the parchment. Negligible distortions across the field are expected in either case.

The camera should have a fixed focus. An adjustable diaphragm may be needed in the case of the line-array approach. Different settings of the diaphragm result in different resolutions and depths of field of the lens. Consequently, a fixed diaphragm system has some significant advantages.

The lens should be thoroughly calibrated for focal length, resolution, and veiling-glare characteristics before installing the system. The optical system, which includes the glass case, will be thoroughly studied in the detailed design phase of this program to mitigate reflections and scattered light problems.

3. Detector

The electronic detector is a transducer that converts light into an electronic signal that can be digitized and recorded. A charge-coupled device (CCD) will be used as the

detector because of its superior stability, linearity, and low noise characteristics.

There are two ways of using the CCD: as an area-array imager or as a line scanner. These approaches are discussed in more detail in Section V. In the area-array imager, a two-dimensional detector array is exposed with a mechanical shutter to a static image of the scene in an entirely analogous fashion to a commercial film camera. In the line-scan imager, a one-dimensional array is mechanically scanned across the scene and read out repetitively each time it advances by one detector element. This type of imaging is primarily used today in commercially available document scanners but is not yet widely used for copying photographic-quality material.

4. Shutter

The shutter controls the time for which the detector is exposed to light from the scene. A shutter is required for area-array imaging but not for line scanning.

To achieve uniformity of exposure across the scene, the time required for the shutter to open and close should be small compared to the total exposure time. To some extent this can be achieved by lengthening the exposure time by reducing light intensity. However, stray light problems limit the usefulness of this solution, and a fast shutter is desirable. An electronic method of monitoring and verifying shutter time and reproducibility is required.

5. Cooling

Cooling of area-array detectors is necessary to limit the buildup of dark current in the several seconds that are required to expose and read out the device. Cooling to $-30^{\circ}C$ is adequate to achieve the necessary dark current reduction. This can be accomplished with currently available, three-stage thermoelectric coolers. The camera head must be vacuum-sealed and periodically pumped to eliminate condensation on the focal plane.

Because the line arrays in line scanners are read off in a fraction of a second, dark current is not a concern; and the detector can be operated at room temperature. This precludes the need for coolers and a vacuum-sealed focal plane.

6. Lights and Filters

The document will be illuminated with incandescent lamps mounted so that they move with the lens detector assembly. Lamp voltages are stabilized to prevent color shift. Precision adjustments are available to achieve optimum lighting angles.

Provision exists for raking and diffuse illumination of the type described in Section II.

Filters can be located on the lamps or on the lenses. In the former case, they are more vulnerable to overheating; in the latter, they may contribute to image degradation. On balance, the location on the lamps is preferred. Spare calibrated filters will be kept in storage.

7. Photometric Calibration

Photometric calibration of the system will be performed using standard pressed polytetrafluoroethylene powder tiles, which have been developed at the National Bureau of Standards recently as a standard of diffuse reflectance (References 4-1, 4-2, and 4-3). The diffuse reflectance of this material is 99% or higher over the spectral range of 350 to 1800 nm. Repeated preparation of pressed samples that have the same reflectance to within a few tenths of a percent can easily be achieved. The reflectance is very insensitive to powder density in the range of 0.8 to 1.2 g/cm^3.

Images of the documents will be referenced to images of the photometric reference sample. No requirement exists for calibration of the CCD sensors for absolute sensitivity although this could be conveniently realized, using self-calibrating silicon diodes developed at the National Bureau of Standards (References 4-4 and 4-5).

C. IMAGE ACQUISITION AND ANALYSIS

The data-acquisition and image-analysis systems are needed to acquire, display, store, calibrate, and analyze images of the Charters of Freedom. The complexity and configuration of such a system will depend on the complexity of the processing, the number of areas to be monitored, and the degree of automatic operation and user friendliness desired for the equipment.

Increasing the number of areas to be monitored places demands on the processing power and data storage capacity of the computer. Enhancing automatic operation and user friendliness places heavy requirements on software. More complexity in the processing and analysis methods affects both hardware and software.

One of the most critical requirements that influenced this study's approach to the image acquisition and analysis system was the need to exploit proven hardware and achieve maximum transfer of existing software. Consequently, in this report there is a survey of current capabilities in image acquisition and analysis systems with the intent that these prove the basis for the detailed design of the image-analysis system. The requirements on

image-analysis software that must be realized in the selected system are discussed in Section 6 and Appendix C.

D. EXPERIMENT DESIGN

Although the hardware, software, and analysis techniques described above are the necessary tools for a successful monitoring program, they must be coupled with a careful experiment strategy. Data will be acquired and calibrated and careful measurements must be conducted to estimate changes extraneous to the document (in the glass case, in the lens, or elsewhere) that might mimic degradation of the document.

Any physics experiment that attempts to detect minute effects or set upper limits on the magnitude of these effects places stringent requirements on experiment design and implementation. This experiment must be carried out under the careful supervision of experts in photometric measurement if it is to be implemented successfully.

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SECTION V

ELECTRONIC IMAGING SYSTEM OPTIONS AND TRADEOFFS

There are several design issues to be considered in the implementation of an electronic imaging system for use in imaging the Charters of Freedom. In this section some of these issues are considered in detail and the advantages and disadvantages of various design approaches are weighed.

A. AREA ARRAY vs. LINE SCANNER

There are two practical design approaches to the imaging-sensing system for the NARS monitoring system. Each has been used in either scientific-imaging or document-scanning applications.

Area arrays use a two-dimensional electronic detector, which is exposed to a focused image of the scene. The image is electronically scanned from the sensor with the sensor held motionless relative to the scene viewed. Line-scan images, on the other hand, use a one-dimensional detector. To provide the second dimension of the two-dimensional image, the linear array must be mechanically scanned over the scene. The scanner is read each time it advances by the width of one sensitive element of the linear array. For the point designs described below, a framing sensor and a line sensor that appeared best suited to the requirements of the application were selected.

1. Area-Array Cameras

The area-array sensor chosen is a Texas Instruments (TI) virtual-phase sensor, a 1024 x 1024-element, charge-coupled device (CCD), which is being developed under JPL contract for scientific imaging applications in planetary science and astrophysics. The principles of operation of CCDs have been described in the literature (e.g., Reference 5-1) and in specific JPL experience with progenitors of this sensor given in References 5-2 and 5-3 and earlier in this report (Section II). This specific sensor is a virtual phase CCD (Reference 5-4), which employs a single phase of clocking pulses to transfer the image from the CCD. It is similar in design to the 800 x 800 sensor used in the experimental measurements program but incorporates a number of design improvements in addition to the larger format area.

Parameters of the selected system are:

Image Pixel:	0.0006-in. square
Image Frame:	0.6144-in. square

Magnifications:	0.4	0.1
Object Pixels:	0.00125-in. square	0.005-in. square
Object Frames:	1.28 in.-square	5.12-in. square

Pixel Time (1):	32 μs
Line Time (1):	34 μs
Frame Time (1):	34 s

(1) Pixel time, line time, and frame time are primarily dictated by the speed of the data acquisition computer.

2. Line-Scan Cameras

The line-scan device used for the line-scan camera point design is the Fairchild 142, a 2048-element linear array CCD. The single line of imaging elements is flanked by two 1024-element serial readout registers, one on each side. When the exposure is complete for one line of the picture, the 2048 charge packets are transferred simultaneously to the two readout registers. Odd-numbered pixels are transferred to the left register and even pixels to the right. The readout registers are under an opaque cover, so the transfer terminates the exposure for that line. The two registers are then read out while the imaging elements are exposed for the next line.

Other parameters of the selected system are:

Image Pixel:	0.0005-in. square
Image Frame:	1.024-in. square

Magnifications:	0.4	0.1
Object Pixels:	0.00125-in. square	0.005-in. square
Object Frames:	2.56-in. square	10.24-in. square

Pixel Time:	20 μs
Line Time:	40 μs
Frame Time:	80 s
Line Rate:	25 per s

The scan could be accomplished in either image or image space. In the former case, the lens and its optical image remain stationary while the detector is scanned through the optical image. The latter case, scanning in object space, requires the lens to move with the detectors. The relative merits of these two alternatives have not been thoroughly studied.

The selected scan mechanism is a ball screw. This device consists of a rotating lead screw and a traveling nut that rides along the screw on ball bearings. The detector would be mounted to the nut. A suitable ball-screw mechanism is commercially available.

The mechanical train consists of a synchronous motor (1800 rev/min), a reducing gearbox (180 to 1), a clutch, the lead screw (2-mm pitch, 10 rev/min), and the moving nut. The scan would be continuous. (The alternative method is step and stare, in which the detector is advanced rapidly by one-line width and then held stationary for the integration time.) The lead screw would carry the detector over the entire 1.024-in. image area in one continuous scan. The peak error in detector position at any point in the scan is calculated to be 0.3 pixel.

3. Comparison of Frame-Scan and Line-Scan Approaches

Table 5-1 shows the major trade-offs between the line-scan and framing cameras. The symbols +, -, or 0 are used to rate each camera type with respect to several important issues.

a. <u>Difficulty/Cost/Risk in Obtaining Detector</u>. The detector for the framing camera would come from Texas Instruments. TI produces by far the largest area-array CCD, and JPL has devoted several man years to improving the stability and noise performance of these devices and understanding its photometric properties. At TI, the choice is between the last of the 800 x 800 detectors and the first of the 1024 x 10024 detectors. At present, the last of the 800s for JPL has been built, delivered, and allocated to users. To obtain a few 800s for NARS, it would be necessary to order and pay for at least two lots of new detector chips and buy a new lot of headers (packages). There is a potential risk here because of the highly variable yield of CCD processing. This could result in no usable detectors (if the yield on two lots were zero).

The 1024 is a new detector. Although it follows from proven technology, it is not yet a proven design. The first developmental units are just now reaching JPL. A developmental unit was acquired in late 1983, and a full quality unit is expected in 1984. The camera will be built around the developmental unit and later retrofitted. The 1024s are attractive because they have a future at TI and JPL, and there is a cost-benefit advantage in joining a large, ongoing activity. However, if all does not go well, the full quality unit could be a year late, and there would be no recourse but to wait.

For the line-array camera, the Fairchild 142 was chosen because it has the required interline transfer readout, and the technical data is already in hand. Other manufacturers make similar line arrays that may be equally suitable. The noise performance of these devices is not well understood but should not be a major design driver.

Table 5-1. Comparison of Frame and Line-Scan Cameras for the NARS Application[a]

Issue	Frame	Line Scan
Difficulty, cost, and risk in obtaining the detector	-	+
Difficulty, cost, and risk in developing the mechanical scanner	+	-
Cooling of detector	-	+
Odd-even pixel differences	0	0
Modulation Transfer Function in the scan direction	+	-
Exposure control via shutter time	+	-
Time to obtain a picture	+	-
Time between pictures	+	-
Document exposure to radiation	+	-
Orientation sensitivity	+	-
Calibration/decalibration effort	0	0

[a]Positive attribute : +
Negative attribute : -
No advantage for either approach : 0

Although the line arrays make possible an image of 2048 pixels by any number of lines, the image would probably be restricted to 2048 square or even 1024 square by the real-time data capacity of the computer. Because the maximum image size that can be conveniently displayed is 512 x 512 pixels, this restriction has little practical consequence.

So the difficulty, cost, and risk are clearly greater for the area array detector, and the + goes to the line array.

b. Difficulty/Cost/Risk of Developing Scanner. The framing camera requires no scanning mechanism although it does

require a set of less accurate lead screws for setting document position, camera position, and focus.

The line-scan camera requires a precision ball screw as described above. Available data indicates that peak scan error can be limited to 0.3 pixels, which is acceptable. The predicted lifetime of the ball screw is also acceptable (one million cycles). There are, however, some timing problems.

The electronic line time is defined as the time between successive transfers from the imaging array to the readout registers and the mechanical line time as the time required for the scan mechanism to advance one line width. For a continuous scan system, these times must be identical. To achieve this, a system might be designed in which the camera clocks (which set the electronic line time) and the synchronous motor (which sets the mechanical line time) are both controlled by the same master oscillator. When the camera is built, however, there will be sufficient tolerance buildup in the gearbox and lead screw to cause a small fixed difference in the two line times. When extended over 1000 or 2000 lines, this small error will become unacceptable.

To correct this error, the system must be modified so that the camera clocks and the synchronous motor are driven by two different but synchronized oscillators. This is a significant problem because it is difficult to synchronize oscillators while providing for small frequency adjustments in one of them.

The alternative of scanning in object space was considered. Because the pixels are larger in object space, a less accurate scanner can be used, but the lead screw must be longer. Another alternative would be to combine the functions of the camera positioner and line scanner into a single ball screw. However, a different gearbox would be required for each magnification: a serious drawback.

The step-and-stare scan method was also considered. With this method, the electronic line time and the mechanical line time are no longer simultaneous and need not be equal. However, the problems of step and stare are numerous. The scanner must stop and start at each line, causing additional vibration. The synchronous motor would no longer work; a stepper motor with digital controller would be needed. The CCD readout would not be continuous, resulting in a noisier video chain and a more complex interface to the computer. The time required to scan a picture is even longer with step and stare.

c. Cooling of the Detector. In a framing camera, the dark current accumulation time is the sum of the integration and frame readout times. For a 1024 x 1024 area detector, this is several seconds. Detector cooling is required to suppress dark

current, and a vacuum enclosure is required to prevent condensation of atmospheric water.

In a line-scan camera, the dark current accumulation time is the line time. In the candidate system, this is 40 ms. Compared to the frame camera, the dark current accumulation time is reduced by a factor of 100, and little or no cooling is required.

d. Odd-Even Pixel Differences. In the frame camera, all pixels are read out through the same serial register. In the line scanner there are two readout registers. There would be an odd-even offset in the raw data. However, because a correction is already required for pixel-to-pixel nonuniformities, no additional effort is required to correct odd-even differences.

e. Modulation Transfer Function Characteristics. In the line-scan camera, the detector moves from one line position to the next during the integration, which results in an anisotropic Modultion Transfer Function (MTF) equal to the framing camera in the cross-scan direction but poorer in the scan direction. Solutions to this problem have been proposed, but the cure is worse than the problem. It is not known how seriously anisotropic resolution would affect the image-processing software. A texture-dependent spatial segmenter might have serious problems.

The sampling characteristics of both line-array and area-array images will result in aliasing of the image detail. Apodizing of the lens to eliminate high spatial frequencies is one approach to correcting this problem but may result in an unacceptable loss of throughput.

f. Exposure Control via Shutter Time. In the framing camera, exposure is controlled by adjusting the shutter time. In the line-scan camera, shuttering is accomplished by the transfer of charge packets to the serial registers. Because the integration time is tied to the mechanical scanner, it cannot be adjusted to set the exposure. Inability to use a shutter to set exposure is a serious problem for the scanner. The lens aperture should also be left fixed to provide best optical resolution and constant focus. This leaves only lamp brightness as a variable to control exposure. Because the Charters must be protected from excessive radiation, even lamp brightness is not a totally free variable.

g. Time to Obtain a Picture. In the frame camera, all lines are exposed simultaneously. In the line-scan camera, the lines are exposed sequentially. Thus, the line scanner will require longer to obtain a picture, but this factor is not considered significant.

In addition, it is not practical to image a time-variable scene, but no requirement for this capability is anticipated (see Section III).

h. Time Between Pictures. For the frame camera, the time between pictures is determined by the frame readout rate into the computer. For the line scanner, the best accuracy will be achieved by always scanning in the same direction. Therefore, the scanner will have to be reset to the starting point between pictures. This is a minor inconvenience unless a large number of pictures is required, for example, during focusing.

i. Document Exposure to Radiation. The frame camera exposes all lines in the picture simultaneously. The line-scan camera exposes one line at a time. Assuming equal integration times, the line scanner exposes the document to 1000 to 2000 times the radiation. However, the levels are not significant in the applications envisaged here.

j. Orientation Sensitivity. The frame camera works equally well in any orientation. The line-scan camera would be designed to scan in a horizontal plane. If the scan camera were removed from the document table to obtain some non-Charters data, scanning in a vertical plane might not work as well.

k. Calibration/Decalibration Effort. The frame camera requires a calibration file equal in size to the total number of pixels in the image: 1024 x 1024. A line-scan camera that scans in object space would require a calibration file equal in size to one line of the picture. With such a small file, the decalibration could be attempted in real time as the data is read out of the CCD.

If the scan were performed in image space, the detector would move through the vignetting pattern of the lens. Thus, the full two-dimensional calibration file would be required. Object space scanning with the line array would not require this procedure.

l. Image Defects. Some pixel defects (short circuits and open circuits) cannot be corrected with a calibration file. A line array with 1024 or 2056 sensitive elements can be screened to be defect-free. For a framing array with three orders of magnitude more pixels, this is impractical.

Although pixel defects represent primarily a cosmetic problem, they do require extra analysis effort to compensate for their presence; it would be preferable to avoid them.

m. Photometric Characteristics and Stability. All imaging sensors exhibit deviations from the perfect transducer of radiation that the designer is looking for. Typically, the more a sensor is studied, the more anomalies are found. No CCD line

array is currently under development as a photometric quality sensor; consequently, less is known about possible anomalies in their behavior than for area-array detectors, which are comparatively well studied. Necessarily, there will be a significant characterization effort to confirm the appropriateness of the preliminary choice of line-array sensor.

It can be concluded from the above analysis that either the line-array or area-array approaches will work. However, the line array appears to be the more satisfactory choice on the basis of the cost and risk of obtaining a detector, avoidance of cooling, and simpler sensor calibration. This choice may need to be reevaluated in the context of new data on the photometric performance of line arrays and the availability and performance of the new TI 1024 x 1024 virtual-phase sensor.

B. COMPUTER CONTROL AND BUFFERING

The CCD scanning device is controlled with a microprocessor. Functions provided by the microprocessor are described in Appendix C.

To achieve the photometric accuracy required for the Charters of Freedom experiment, it is essential that the image be read synchronously from the sensor at a constant, uninterrupted rate. This can be achieved in a variety of ways. The choice is a significant factor in the design of the image-acquisition system.

One approach is to read the digitized scanner data into a scanner buffer (a random-access memory from which data can be transferred asynchronously to display processor memory, computer memory, or disk when those devices are ready to receive data). This approach has the disadvantage of requiring a partially redundant memory for providing the synchronous transfer capability.

Alternatively, data can be transferred directly to the display processor memory, which allows memory resources to be used more efficiently and has been implemented successfully on a JPL imaging scanner. However, this technique requires a specialized hardware interface and necessarily interferes with any concurrent display or image-processing operation that uses the display processor.

A third possibility is to transfer data to the random access memory of an image-processing computer via one of the standard I/O channels of that computer. This allows memory resources to be used efficiently, avoids interference with display operations, and does not require special purpose interface hardware. However, it does mean that the image-processing computer operating system (and possibly the executive also) must have a real-time

capability that would allow other I/O operations to be disabled during the scanner-read operation. In addition, the computer must accommodate sufficient memory to store an entire image and sufficient I/O channel capacity to accept data at the scanner rate.

The choice depends on whether the image processing is colocated with the electronic image-acquisition system at NARS and on the suitability of display processors for direct acquisition of data.

C. FOCUS CONTROL

Experience in the experimental measurements program indicates that focusing the camera on the document is one of the more difficult and one of the most important operations to be performed. Each monitoring measurement must be performed with the camera at the same focal distance, or spurious fading effects could be obtained.

1. Focusing Problems

Several focusing problems surfaced during the experimental measurements program:

(1) Several minutes are required to reposition the lens, acquire an image, and display that image. Consequently, iterative manual focusing operations are time consuming.

(2) There is far too little high spatial frequency detail in an image for satisfactory focusing when that image is obtained with diffuse lighting conditions at 800 lines per inch. However, it was found that raking (low) incidence illumination highlights parchment texture and provides satisfactory image quality for focusing.

(3) Parchment surfaces are not flat but undulating; therefore, an entire image area is not simultaneously in focus. The out-of-focus problem will be less severe for the Charters of Freedom than for the Petition and Memorial of Freemen. A glass plate, which is in contact with the former documents, reduces the amplitude and undulation. However, this is still a concern.

2. Focus Control Methods

Some approaches to focusing and obtaining a repeatable focus are described below.

a. Auxiliary Microscope. With this approach the initial focus would be obtained by the manual iterative procedure used during the experimental measurements program. Once that focus was established, an offset distance between the lens and the parchment would be determined, using a microscope that has a much smaller depth of field than the lens of the electronic imager. The microscope and electronic imaging lens are bore-sighted and mechanically attached to one another and can be translated vertically, using a lead screw with an accurate vertical scale.

For subsequent measurements, the microscope would be initially focused on the parchment and translated by exactly the same distance determined earlier to place the electronic imaging system in focus.

The advantage of this system is its comparative simplicity. A disadvantage is that the microscope and camera cannot look at the same piece of parchment with purely a vertical translation. A horizontal translation is also required, which may introduce some operational complexities.

b. Automatic Focusing. With this approach, the scene data from the electronic imaging sensors would be sampled to determine the level of scene activity and the lens position automatically moved to a position providing higher scene activity and better focus. The principles underlying this approach are discussed in Section II.

Although this method has some obvious advantages, it does require a closed-loop control system involving the analysis of image data from the camera. This would place additional demands on the software, entail significant additional cost, and increase the mechanical complexity of the scanner system.

The preferred approach is to use the auxiliary microscope with provisions for frequent calibration. However, software should be implemented for analyzing the variability of scene activity through the plane of best focus.

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SECTION VI

IMAGE ANALYSIS

A. ALTERNATIVE APPROACHES

Three alternative approaches to the analysis system for the Charters of Freedom have been examined. The three approaches differ in various respects: the power of the imaging-processing system that is provided to NARS, the complexity of the hardware components, and the comprehensiveness and sophistication of the image-processing software that operates on the system. The three approaches are described below.

1. Option A: Minimal System

With this option the image-processing tools provided in the system at NARS are limited to those that are needed to display a "raw" image from a CCD camera and verify that it is properly focused. However, raw images from a line-scanner option (see Section V) could be photometrically decalibrated, enhanced, and displayed with this system. Raw images from the area-array imager option would have to be recorded on magnetic tape and photometrically decalibrated at JPL. All digital analyses of photometrically corrected imagery would be conducted at JPL from either type of imager.

2. Option B: Basic System

With this option, a basic image-processing system would be provided to NARS. Initially, at least its capabilities would be limited to performing photometric correction of Charters of Freedom data before its transmittal to JPL for analysis. However, within 2 years it should be possible to develop at NARS the necessary software tools to analyze the Charters of Freedom experimental measurements. Before that time, however, the image-processing system could be used for scientific applications that do not require the extreme photometric precision and elaborate experimental protocols needed for the Charters of Freedom experiment.

3. Option C: Comprehensive System

This option would provide a complete software system for supporting monitoring of the Charters of Freedom at NARS at the time the monitoring process begins. It would be capable of implementing calibration, decalibration, and analysis operations in a highly automated fashion, thereby reducing the demands on the skills and scientific background of the operator. These capabilities would go far beyond the routine modular, image-processing operations provided in Option B.

Table 6-1. General Requirements for NARS Image-Analysis Systems

Item	Option A Minimal System	Option B Basic System	Option C Comprehensive System
Image-processing software			
Operating system			
Existing software	Mandatory	Mandatory	Mandatory
User friendliness	Yes	Depends on executive	Depends on executive
Transportability	Not required	Not required	Not required
Real-time capability	Yes	Yes	Yes
Executive			
Existing software	Not required[a]	Yes	Yes
Transportability	N/A	Not required	Not required
User friendliness	N/A	Yes	Yes
Supports 32-bit virtual memory	N/A	Yes	Yes
Application programs			
Image acquisition	Yes	Yes	Yes
Display	Yes	Yes	Yes
Analysis	No	Yes	Yes
Procedural control of analysis	No	No	Yes
General purpose image processing	No	Yes	Yes
Application Program Library	No	Yes	Yes

[a]It may be possible to avoid an executive entirely for Option A and rely on operating system functions. Otherwise, image-display capabilities may be incorporated with camera-control function.

To assess the feasibility and comparative merits of these options, it is useful to provide some of the technical background on the design of image-processing and analysis systems, including recent developments in this rapidly moving field. This background and experience will be useful in any system chosen for implementation.

B. IMAGE-PROCESSING SYSTEM CONCEPTS

1. Hardware

A block diagram of a general purpose image-processing system appears in Figure 6-1. The hardware components of the system and their functions are as follows:

(1) The <u>central processing unit</u> (CPU) is the "brain" of the image-processing computer, functioning as an interpretor and executor of instructions. It is capable of performing several million operations per second.

(2) The <u>computer main memory</u> is the storage bank of instructions (programs) and data. Data and instructions must be resident in the main memory before the CPU can access it. The amount of main memory available may range up to several megabytes. This depends on the system requirements.

(3) <u>Mass storage</u> is an additional storage bank for programs and data not currently needed by the CPU. However, when needed, it can be read into the main memory. This device is generally a "hard" disk. The capacity of disks may range from tens to hundreds of megabytes.

(4) The <u>offline storage/archive</u> is typically a tape drive that will allow the user to record magnetically and archive data files that are not needed all the time or that must be archived. Because there is a finite amount of storage with both main memory and mass storage devices, it is necessary to off-load this data onto another storage device.

(5) The <u>display processor</u> is designed to accept digital image data from the computer (or in some designs from the CCD camera directly) at typical computer input/output rates (<1 megabit/s), store them, and refresh a video display at the high data rates needed by standard television monitors (50 megabits/s).

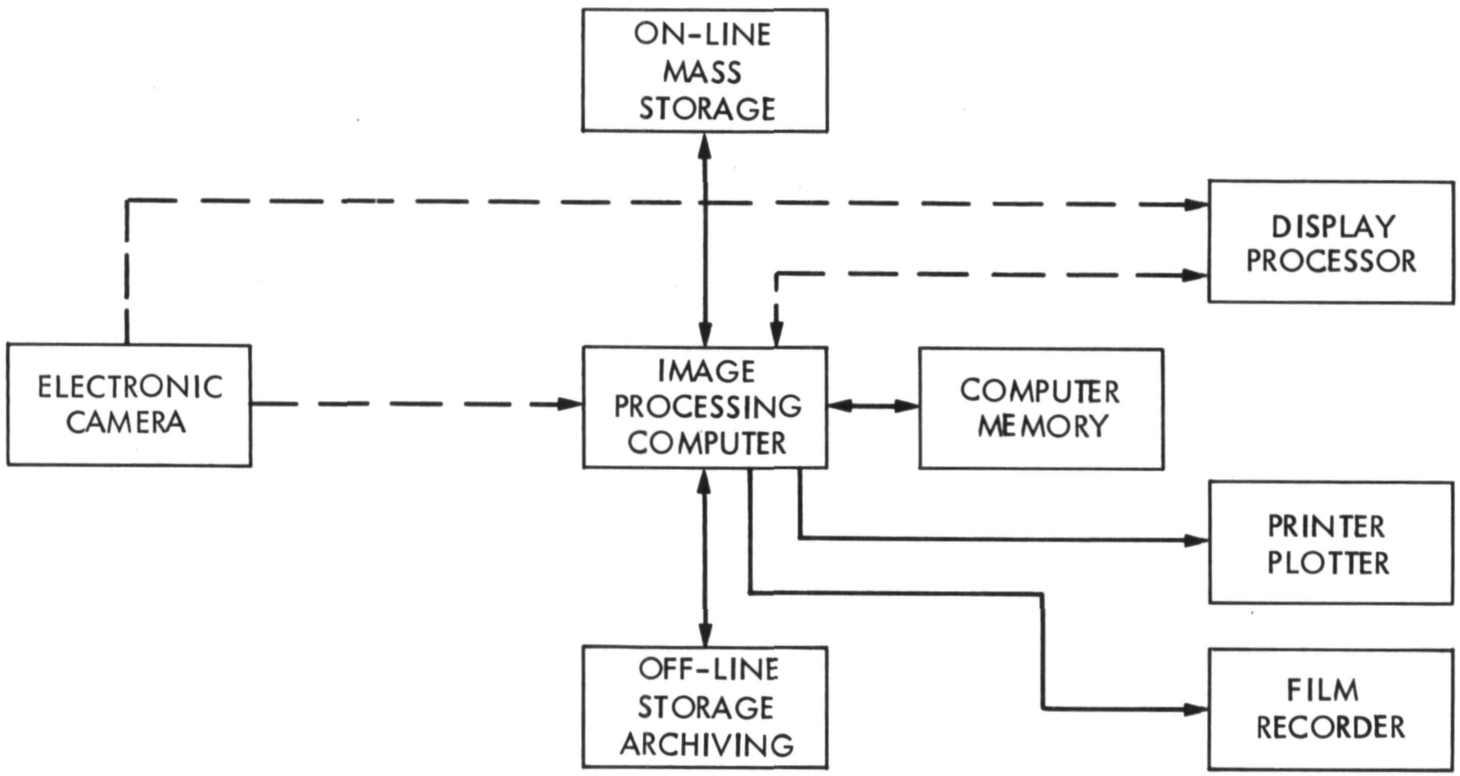

Figure 6-1. Block Diagram of Image-Processing System Interfaced to Electronic Camera

Many modern display processors also allow the user to conveniently obtain positional and intensity information for the displayed image, using interactive devices such as joysticks and trackballs, and to superimpose alphanumeric and graphical information on the displayed image.

(6) The <u>film recorder</u> accepts digital image data from the computer and forms a high-fidelity photographic record on polaroid or conventional photographic film.

(7) The <u>electronic camera</u> acquires an image of the scene viewed (Section V-A). There are various alternative approaches to transmitting the image to the image-processing system, which are considered in Section V-B.

2. Software

The computer software is the complex set of instructions that prescribe the particular tasks that the user must perform. A key factor in selecting the specific computer to be used in an image-processing system is the availability of software, which is expensive to develop. For this reason, one looks for computers with an extensive complement of existing software and software tools that simplify the development of codes for the particular specialized application.

Image-processing software can be grouped in a hierarchy of three major components: operating system, executive, and application programs. The function and the availability of software for each component of this hierarchy is discussed below. These considerations apply, although in somewhat different ways, to data processed in systems located at NARS and at JPL and are critical to evaluating Options A through C.

a. <u>Operating System</u>. An operating system is the basic interface the user has with the computer. It allows the user to perform input and output of data, assign files and devices, and execute system utilities and user programs. It also provides system-error messages. Operating system features that are potentially important to image processing are user friendliness, transportability, and real-time capability.

(1) A <u>user-friendly</u> operating system will provide the user with an environment that is easy to understand, having simple command formats, clear diagnostic messages and effective help facilities. Some recommended user-friendly operating systems are VAX/VMS, PRIMOS, and UNIX.

(2) A transportable operating system will run on a variety of computers produced by different manufacturers. The extended UNIX system is transportable and is used on a variety of computers. Both VAX/VMS and PRIMOS have only limited transportability because they are restricted to use on the VAX and PRIMOS series of computers, respectively.

(3) Some operating systems such as VAX/VMS and PRIMOS, but not UNIX, have a real-time capability that may simplify transfer of data from the CCD camera to the image-processing system. The CCD camera must output an image in a continuous, uninterrupted stream; otherwise, anomolies and random signal effects appear in the scanned image. A computer with a real-time capability is able to accept a continuous uninterrupted stream by suppressing all other demands for service during the camera readout period. Of course, the computer must have sufficient memory to store an entire image and sufficient data channel capacity to accept the data at the rate at which it is supplied by the camera.

b. Image-Processing Executive. An image-processing executive is a software package that provides the operating environment and specialized services required for efficiently performing image-processing. Usually, it coexists on the computer with the operating system but supplements and, in some cases, entirely replaces the functions of the operating system. Typically, image-processing functions handled by an executive are file-and-device assignments, parameter assignments, and program executives. A transportable executive, when implemented on different computers with different operating systems, provides the user with an environment that is independent of the machine and operating system.

The advantages of using an executive are that it simplifies and standardizes system use and facilitates program development. There are some disadvantages: executives tend to increase execution time and memory requirements, and they preclude the use of special features of a computer or operating system that promote efficiency. If the image-processing application involves a rudimentary set of functions that must be performed on a small machine with limited memory and processing resources, then the overhead (in terms of time, memory capacity, etc., of the executive) may override any benefits it offers. However, where needed capabilities are more extensive and where the possibility of growth is desired, then an executive is mandatory.

The following image-processing executives are available at JPL: VICAR, MINIVICAR and TAE.

(1) Vicar was designed to execute on the IBM/370 mainframe for the Image Processing Lab at JPL. This Executive is not easily transportable to non-IBM computers. It will be phased out during the next three years at JPL and be replaced by TAE.

(2) Mini-Vicar was designed to run on the LSI-11 and PDP-11 computers. However, it is not a true Executive with an Executive command language and restricts images to 8-bit format. This is unacceptable for the NARS application because the images will be represented at a 12-bit/pixel resolution. It is also specifically tailored to the 16-bit PDP-11 series of computers, which are now obsolete. Currently, 32-bit virtual memory machines are the systems of choice for image processing.

(3) The Transportable Application Executive (TAE) is designed for use on a variety of computers, including modern 32-bit machines and was originally developed by Goddard Space Flight Center (GSFC). It is currently in its formative state and being developed for the VAX/VMS system. JPL is implementing the Executive on its new VAX computers for the Multimission Image Processing Laboratory (MIPL). There are also plans to implement the Executive on a new class of powerful microprocessor-based work stations, including systems using the popular Motorola 68000 microprocessor. Because this Executive is still in the developmental stages, it lacks full executive features. To date, it provides a user-friendly environment offering both help and tutor modes.

A program executing under the TAE must have a help file associated with it to document the program and a parameter-definition file to assign parameter defaults and definitions. It limits the number of parameters accepted, and there is no provision as yet to assign parameters values via a separate parameter file. There is also no command language for acquiring, copying, or deleting a file except by going through VAX/VMS; and tape files must be managed differently from disk files, which is inconvenient for an image-processing system. Finally, there are no standard routines for interfacing to display processors and film recorders. Fortunately, these deficiencies in TAE are being addressed as part of its adaptation to provide the Executive for JPL's Multimission Image Processing Lab (MIPL).

c. Application Programs. An application program is a computer code that implements a specific image-processing task such as contrast enhancement, photometric correction, or geometric transformation. A mature and well designed image-processing system provides an extensive library of existing application programs and the facilities for rapidly developing new special purpose application programs. An application program is written using the facilities provided by the operating system and the executive.

The ease with which applications programs can be developed is dependent on the services provided by the operating system and executive. Some executives and operating systems provide the capability of chaining several application programs and implementing them in either interactive or batch modes. Application programs written under one executive can sometimes be converted to operate another. Currently, an extensive family of application programs exists for use under the VICAR executive, a much smaller number for MINIVICAR, and a small, but rapidly expanding group, for TAE. Much of the TAE application program family will be converted from VICAR application programs.

Most of the other operations needed to monitor the Charters of Freedom will require specialized application programs tailored to that task; therefore, the extent of the library of existing software is not of concern in that regard. However, an extensive library of software would be an asset for handling of non-Charters applications, as discussed in Section III.

C. REQUIREMENTS FOR IMAGE-ANALYSIS SYSTEMS

Three system approaches to the image-analysis needs of the NARS Charters of Freedom monitoring task are described in the introduction to this section. There are also specific requirements for each approach using the conceptual framework developed above.

Some general qualitative requirements imposed on the three analysis approaches have been identified. One repetitive theme that appears in these requirements is the need to use mature hardware from major manufacturers to assure reliability, servicing, and a long operational life (Appendix D). Another is the need to use existing operating systems, executives, and application software packages to avoid costly and time-consuming software development (Table 6-1).

D. IMAGE-ANALYSIS SYSTEM POINT DESIGNS

Hardware and software point designs for Options B and C can be quite similar but differ markedly from those for Option A. An evaluation of suitable designs for Option A is given in Appendix C. An evaluation of suitable hardware systems for Options B and

C is given in Appendix D. The choice of operating system and executive is shown to be inextricably tied to the hardware choice. Point designs for the image-analysis system are described in detail in the implementation plan.

SECTION VII

SUMMARY AND RECOMMENDATIONS

This report describes a conceptual design of an electronic imaging and image-analysis system for monitoring the Charters of Freedoms and also examines some of the experimental problems involved in detecting small changes in these encased documents. Certain issues in the design of the system, however, are not resolved in this report. They include the type of CCD imaging sensor to be used (area array or line array) and the capacity and flexibilty of the digital image-analysis system. Cost factors not covered here will enter into both decisions, and these decisions can be made after the completion of an implementation plan.

In the detailed design phase a number of important issues are addressed:

(1) A detailed analysis of scattering and reflection from glass surfaces in the case should be conducted. An imaging configuration should be devised that minimizes these contributions to the light arriving at the image plane and that allows the magnitude of the component to be measured.

(2) An analysis of the effect of sampling in discrete, non-overlapping pixels on measurements of contract and comparison of images acquired at different times should be carried out. Subpixel magnitude shafts in the sampling pattern of an image containing high-frequency detail results in substantial changes in the sampled image due to aliasing. Because apodizing of the system to reduce high frequencies may be difficult, the magnitude of the effect of not apodizing the system should be assessed.

(3) Choice of imaging detector (area-array vs. line-array) should be finalized and a detailed design for camera mount, camera head, optical system, and lighting system completed.

(4) A detailed, end-to-end study of the ability to detect changes in the document should be implemented. This study should incorpoate all the factors considered above. An estimate should be made of the sensitivity of the experiment.

(5) Electronic camera measurements should be carefully integrated with conventional photographic measurements to provide a comprehensive monitoring program of complementary measurements.

(6) A decision is needed about how many areas should be monitored, in how many wavelength bands, and how frequently. With this information, the size of the computer system needed for monitoring can be scoped.

APPENDIX A

CONSERVATION EXAMINATION OF THE PETITION AND MEMORIAL OF FREEMEN DOCUMENT

A. INTRODUCTION

The CCD Experimental Measurement Plan for the National Archives and Records Service (NARS) Task is part of an overall program to determine the best method of measuring the state of preservation of the Charters of Freedom. This plan has two major parts: 1) imaging of a dummy document and 2) imaging of the Petition and Memorial of Freemen (PMF) document. As part of the PMF imaging study, both detailed photography and an examination of the physical condition of the document have been undertaken with attention toward isolating problems, which may be active or could be active under adverse environmental, handling, or display conditions in the future. This report is the result of that examination.

B. BACKGROUND DISCUSSION OF PARCHMENT AND VELLUM

Historically, the process for making parchment and vellum has been traced to Emperor Eumenes II at Pergamum in Asia Minor about 190 B.C. According to the story, Eumenes II needed a substitute for papyrus, recently denied him from Egypt, to support his vast library. As fascinating a story as this makes, it is now evident that the lime treatment of parchment and vellum existed earlier than the 2nd century B.C.

The terms "parchment" and "vellum" are often used interchangeably today, but this is not strictly accurate. Vellum, the finer of the two skins, is the unsplit skin of a young calf that has been cleaned of adhering fat, muscle, hair, or flesh; has been soaked an aqueous lime solution; and has been carefully scraped and polished. The finest vellum, usually reserved for the most precious books or documents, was made from unborn calves or, later in the Middle Ages, the stomach lining of oxen. Parchment, on the other hand, was made from the skin of sheep, ewes, or lamb; but many other skins were tried, often with macabre results.

To distinguish parchment and vellum from other skin products: Parchment and vellum are lime-treated, leather is tannic-acid-treated, and tawed skins have been alum-treated (usually potassium aluminum sulfate, but potassium sulfate and chromium salts have been used).

Some of the conditional problems that affect parchment and vellum are cockling and embrittlement caused by dehydration/hydration cycles. Some dehydration effects produce a "horny"

character that can be directly attributed to the loss of water, which serves as an interstitial lubricant. Because this loss can be regained, water and alcohol/urea solutions will return some flexibility. However, two causes of embrittlement remain: The loss of essential oils, which have been treated with lanolin or spermaceti oils, and a polymeric dehydrative loss of molecular water, which has not been completely explored.

Additional problems that have been cited in the general conservation literature can be easily summarized.

(1) Limits set for total illumination of 5 footcandles or 50 lux taken as footcandle-lux/hours days, etc. This value being adjusted to compensate for RPDF, Relative Probable Damage Factor (after Harrison), which takes into account the spectral distribution and that distribution's total effect on chemical alteration for the sensitive material in question. RPD usually seeks to establish the contribution of energies capable of disrupting either chromophoric bonds (fading), important cross-linking (embrittlement), or establishing new cross-linking (insolubility).

(2) Limits for relative humidity fluctuations, given as 45 to 60% maximum, or 50 to 60% preferred. Higher and lower values cause internal stress to be redistributed. Such redistribution is X, Y, Z normal. If one direction is restricted, stresses will equalize regardless, possibly causing damage.

(3) Acidic hydrolysis. This can be caused by ink manufacture or environmental intervention. Acidic inks that have high sulfuric acid content will degrade fine skins with inadequate buffer. Sulfur dioxide has had a well-documented effect. High levels of anthropogenic sulfur dioxide combine with and are catalyzed by both transition metals (i.e. iron, copper, manganese, etc.) and moisture to produce sulfur trioxide and sulfuric acid. This is an immediate attack.

(4) Parchment and vellum cannot be made immune to insect, micro-biological, and rodent attack. The literature is in agreement in recommending well-fitted lids for all storage containers.

(5) The last major problem remains a near-fatal irony: inept handling, incomplete knowledge, and panic by well-meaning individuals under extreme conditions.

C. GENERAL DESCRIPTION AND MOUNTING

The Petition and Memorial of Freemen (PMF) is a parchment document with an overall length at the left edge of approximately 1567 mm (irregular) and approximately 611 mm along the top edge. It is composed of three sections, the top section measurement at the left edge is approximately 638 mm, the middle section approximately 742 mm, and the bottom section aproximately 192 mm.

The three sections are joined by stitching with thread (probably linen) and possibly at some point previously joined with an animal glue/gelatine adhesive (described below). The joint between the top and the middle sections has been executed with two horizontal lines of stitching about 2.5 to 5 cm apart. Where each row of signatures has been separated into vertical columns by ink lines, vertical stitching has augmented the horizontal stitching. The method is a simple over-and-under type of stitch. The verso is without adornment.

For purposes of CCD imaging the PMF document needed to be mounted vertically. To this end a moveable rigid support was constructed by the JPL carpentry shop to support the PMF by a means conducive to good conservation practices. To facilitate that mounting a three-part Cellotex folding panel was produced with each section, approximately falling where the current major folds in the PMF ocurred. The first section was 67.5 cm long, the second approximately 56.4 cm, and the last section approximately 53.3 cm. To provide added support, the Cellotex mount was a two-ply construction with a thin sheet of aluminum between the sheets. Hinging between each section, which could fold easily back and forth, was provided by a fine metal mesh incorporated within the lamination. Hinging edges were beveled, and the whole support was held with powerful magnets to a stainless steel table bed. Additional doweling was also used when needed.

One problem that developed resulted in unacceptably high dust levels caused by the untreated Cellotex edges. This problem had not been previously anticipated, but due to the large number of "artifacts" that appeared on the CCD images, it is safe to say that even this slight added dust contribution should be removed. In the future, the edges will be sealed with an appropriate methacrylate polymer such as Rhoplex AC-33 or a (poly)-vinyl acetate emulsion.

The PMF was mounted so that the document could easily slide, stress-free, while being positioned. Both sides had been enclosed within Mylar envelopes, which in turn was secured to the Cellotex with push-pins. To support the central regions, polyethylene "tubes" spanned the document and were secured in the same manner as the Mylar.

D. SPECIFIC CONDITION PROBLEMS

Normal Lighting Examination

The PMF document was first examined under ambient lighting conditions, which ranged between 4 to 8 footcandles over the entire surface area, as specified by NARS. This proved too low for an effective evaluation in some cases, so, in accordance with common conservation examination practices, those values were raised during some parts of the final examination. The highest footcandle incident exposure never exceeded 20 footcandles. This latter value can be shown to fall below a 10 footcandle/hour total irradiation limit, which is identical to the NARS specification. It should further be pointed out that these higher levels were the only means of producing good "raking light" conditions needed to evaluate the relative stress-dependent deformations of the document.

2. General Classes of Conditional Features

The following general classes of conditional features were determined:

(1) Insect/mechanical damage.

(2) Fading and/or color shifts in different inks.

(3) Flaking of inks.

(4) Stress-dependent deformations, including

(a) Splits

(b) Stitching

(c) Possible storage-related cockling

(5) Soiling at left edge.

(6) Trimming along right edge.

(7) Micro-biological discoloration.

(8) Foxing, micro-biological, or transition metal deterioration.

(9) Overall large-area yellowing.

(10) Large-skin imperfections.

(11) Old folding lines.

a. Insect/Mechanical Damage. There are three areas of damage that are probably of insect origin but could also have been mechanically produced. In the central section of the PMF document at the left edge, the damage can be seen as irregular holes in the skin. The first area is located near the junction of the top and middle sections. This area is complicated to interpret because there are several kinds of deformations evident, but the losses are probably insect caused. The second area, which comprises three distinct holes, is 5 to 7 cm above the bottom major fold. These are fairly clean. The last region is just below the bottom major fold and appears to have been repaired, or the fold has been reinforced and part of that effort can be seen through the bottom series of 4 to 6 very minor holes.

b. Fading and/or Color Shifts in Inks. There are at least four inks that have distinct colors, and there may be as many as six. The most striking ink has a reddish hue, which appears to have faded the most. Secondly, there is an ink that can be seen at the bottom of the first column. This ink seems to be less red but also altered. It seems to be of lesser quality, as witnessed by the blotchy character of the last 14 signatures. Compare these signatures with the fine pen lines produced with other pen/ink configurations within the document. A third type of ink might be represented by the general text of the document's uppermost and bottom sections. A fourth ink may be seen in the region just above the three "insect holes" at the left margin. Here the ink is very dark brown and may only be slightly changed over time.

c. Flaking of Inks. Flaking is a general problem. Each vertical column line has significant flaking, and in these lines two sub-types can be identified: (1) a clean delamination leaving almost no trace of ink or discoloration and (2) losses that appear to leave a stain.

Within the body of the signatures many examples of flaking can pointed out, notably in the second column below the lower major fold (here under slight magnification one can see where small flaking ink chips have been re-adhered in adjacent areas, possibly caused by the combination of long-term moisture and the pressure of being folded and stored under weight). Also, major flaking is evident below the upper major fold, particularly in letters with denser ink deposition.

d. Stress-Dependent Deformation. There are many deformations of the PMF document. Stitching at the joint between the middle and bottom sections seems to suggest tension in the past, and under raking light illumination, the bottom edge of the middle section has the same cockling as that characteristic over the entire bottom section in an area and extent that cannot be

correlated with any form of current attachment. This may indicate that these distortions are very old and give evidence of previous attachments, while the stitching is much newer in age. Also at this joint, the linen tread may be pulling the document substrate. The edge below this stitching is folded up; no explanation offers itself.

Under raking light, the characterization of the middle section of the document is complex and beyond the scope of this examination. We asked the conservation staff of NARS to assist in the explanation of these many features as the CCD imaging study progresses.

At this point in the study we can point out that the lower 40% of the central section is remarkably flat as compared with the remainder of the document. The upper portion shows cockling, which indicates that the skin has been permitted to conform to any shape its hygroscopic character demands; yet the bottom portion of the middle section has not been so permitted. Interestingly, it is only in this region that the "splits" appear. (These "splits" do not look like cut marks because they do not go through the document; they are rather more like separations in the upper strata of the skin. Also, these splits appear as the more aggrevated section of longer sharp folds. These folds are short and occur without apparent reason.)

The PMF document has 14 to 16 "splits." This condition is possibly currently stable, but that stability cannot be expected to remain with rapid changes in atmospheric humidity, which alter the moisture content of the skin itself. Because the exact cause is not known, a corrective suggestion cannot be made.

e. <u>Soiling at the Left Edge</u>. Soiling at the edges, which is normally the product of handling, is evident at the left edge in the middle section. Soiling at the right edge may have been trimmed off.

f. <u>Trimming</u>. Looking at the text in the top section, one can see a margin on the left edge while the text runs off the document's edge at the right margin. This condition is identical in the bottom section. If one looks more carefully, there is evidence of trimming from another direction. Both at the left and right edges the skin flares outward at the bottom major fold. Now, if the document is folded up, the edge below the fold is roughly congruent with the edge above. This suggests that those edges were trimmed while the document was in its folded state. These comments equally hold for both sides but not necessarily for regions of the document towards the top section.

g. <u>Microbiological Discoloration</u>. Mirobiological attack, whether it is caused by mold or fungi, is a common problem in any historical document on paper, parchment, or vellum when

storage conditions exceed 70% relative humidity over extended periods of time.

In the PMF document evidence of microbiological growth is limited largely to an area in the bottom section, along the right side, approximately 160 mm in, and extending to 260 mm, roughly 180 mm from the bottom. Also visible is an area approximately 160 mm from the left edge, 35 mm wide, and from 100 to 160 mm from the bottom edge.

h. Foxing. Foxing is a general term that describes mottled, yellowing, or reddish or red-brown spots distributed over the surface of a document or work of art. The origins for foxing are not well known, yet both bacterial activity and metal particle inclusions have both been cited as primary causes. Without going into the chemistry of metal species oxidative deterioration, it may be said that any spot that exhibits these characteristics is probably unstable in high relative humidity conditions.

i. Overall Large-Area Yellowing. Under normal lighting is appears that the upper half of the document has survived better than the lower half. As one begins to examine the document, scanning downward, a large area of slight yellowing begins to appear. One possible hypothesis, keeping such things simple, is that for decades the document was stored in its folded form. Evidence will be presented that further describes its previous folded format yet, for the present, any folding in conditions of moisture would tend to favor drier folds being on top with greater moisture retention below in the lower folded sections. The exception is the bottom section, which nevertheless appears to be added on.

Furthermore, the area between the first and second section, which has been stitched together, also looks discolored. This discoloration, a more yellow-pinkish, might be due to the document being glued together at some point. The gentle insertion of a small flat spatula between the two sections was helpful but inconclusive.

j. Large-Skin Imperfections. These imperfections need further work. They appear at the bottom corner, below the bottom fold at the right margin, and near the joint between the top and the bottom sections.

k. Old Fold Lines. The PMF document was probably folded much differently during the early years after its creation. Slight horizontal folds can be seen under raking light conditions that are distinct enough to provide dependable evidence of its previous storage. The position of these folds is described in Table A-1.

Table A-1. Fold Position and Spacing

Fold Position	Fold Spacing, mm	
	Individual	Overall
1	194	194
2	170	365
2a	15	380
3	205	585
4	180	765
5	90	855
6	95	950
7	120	1070
8 and 9	Near bottom, unmeasured	

E. SPECIFIC CONDITION PROBLEMS

Ultraviolet Light Examination

Under ultraviolet (UV) inspection the docment fluoresced differently in each of its three sections. The top section fluoresced purple-white, in direct contrast to the middle section, which fluoresced much more brightly cream-white, with the aforementioned, yellow-brown, large-area discolorations being bright orange. The bottom section appears intermediate between the other two sections. From this evidence it seems hard to imagine that the three pieces may have come from the same skin, or were even prepared identically. The UV fluorescence properties of the PMF document are striking, and there may be a possibility of characterizing the skins more precisely. For the purpose of this study, however, such characterization is not required, yet it is suggested that NARS investigate this kind of evidence further.

Although many of the signatures have faded, none are irretrievably lost. Even the most faded inks have lost little of their UV-quenching properties. Thus, in UV they appear as black lines against the bright parchment fluorescence.

No other significant features were detected under UV.

F. CONCLUSIONS

The following characteristics can be considered unstable under adverse environmental, handling, or display conditions and are hence important to image.

(a) Fading or color shifting of inks. This would be manifested by a change in contrast between adjacent signatures and between ink and skin.

(b) Flaking of inks. This is the most likely change to detect easily and is caused largely by mechanical stress in handling. In addition, humidity-caused stresses will increase this problem.

(c) Extention of the "splits" at the bottom of the middle section (raking light). As the cause is not well known, prudence justifies accepting these as presently active.

(d) Movement in regions of stitching.

APPENDIX B

TECHNIQUES FOR MEASURING READABILITY

This appendix is concerned with the development of quantitative techniques for determining readability of lettering (penstrokes) on parchment. These techniques were evaluated using digital CCD images acquired in the Experimental Measurements Program described in Section II. Here the procedures used for processing these data are described, and the alternative techniques for characterizing readability are evaluated. However, preparation of the test data is described first.

A. PREPARATION OF IMAGE DATA FOR ANALYSIS

To perform digital manipulation of the CCD image data it was necessary to convert the image records on computer tape recorded with the CCD sensor test set (STS) to a form compatible with the VICAR digital image processing system used at JPL's Image Processing Laboratory (IPL).

A digital image-processing system manipulates digital images, which are image representations in the form of arrays of numbers. In JPL's Image Processing Laboratory an executive software system (see Section VI) called VICAR is used. VICAR provides a modularized computer language and over 300 general and special purpose application programs.

The preprocessing and decalibration operations needed to prepare the CCD images for scientific analysis follows.

1. Preprocessing

The 420 images from the CCD STS were converted from the recorded 6250 bpi (bits per inch) density to 1600 bpi at JPL's Woodbury facility so that they could be input into the IPL system. They were originally recorded at high density as a time-saving measure during experimentation.

The 1600-bpi images were converted to VICAR format in the IPL. Each image was assigned a title. Eighty selected images were masked out, using a process described later, converted to the form of photographic hard copies, and bound to provide a reference set of images for processing.

2. CCD Decalibration

Two light-transfer sequences, bracketing the period of PMF imaging, were acquired with the STS. These were acquired by illuminating the CCD with uniform, unfocused, broadband light. Three images were acquired at each of eighteen different exposure

levels, spanning the range from the CCD noise floor to full well, the lowest to the highest recordable signal. The purpose of the light transfer sequence is to measure the response of the CCD to an input signal and store that response so that it can be used to "decalibrate" images taken with the CCD. The decalibration process removes the response signature of the CCD from the scene. Each pixel in the CCD has its own distinct response characteristics. Hence, the decalibration file that is created from the light-transfer sequence contains a separate entry for each of the 640,000 pixels in the CCD array.

Computer software developed for the Galileo project was used to create the decalibration file from the light-transfer sequences. The three images at each of nine selected exposure levels were averaged and then used to characterize the pixel response. Over nearly all of the dynamic range the response to light is very linear, falling graphically on a straight line of positive slope (Figure B-1). A slight low-level nonlinearity was discovered, which complicated the processing considerably. It apparently was caused by a slight misadjustment of the CCD operating voltages. It will only affect pixels that are so dark as to be near the dark current level. None of the images of the PMF that were analyzed contained such pixels. A work-around was implemented, resulting in the decalibration file shown in Figure B-2. In this image the photometric response characteristic of each pixel is coded in terms of brightness. Each pixel has its own distinctive constant. A perfect sensor would display as a uniform, flat gray tone. The bright and dark areas in the display of this real sensor's characteristics correspond to pixels whose behaviour is anomalous relative to the characteristics of surrounding pixels.

In cases where multiple exposures of the same scene were taken, image averaging was first performed to increase the signal-to-noise. Then the decalibration file was applied to remove the pixel-to-pixel response variation described above. The last step prior to image-processing experimentation was to remove the illumination nonuniformity caused by spatial variations of the lamp illumination.

The images of the white photometric tile that were acquired coincident with the target images are used to remove this shading in the following manner:

$$R.U. = (PMF-DC) \times K/(T-DC)$$

where the final image is calibratible in reflectance units (RU), a dark current (DC) image is subtracted from the PMF document and tile (T) images, division is performed, and the result is scaled by a multiplicative constant K.

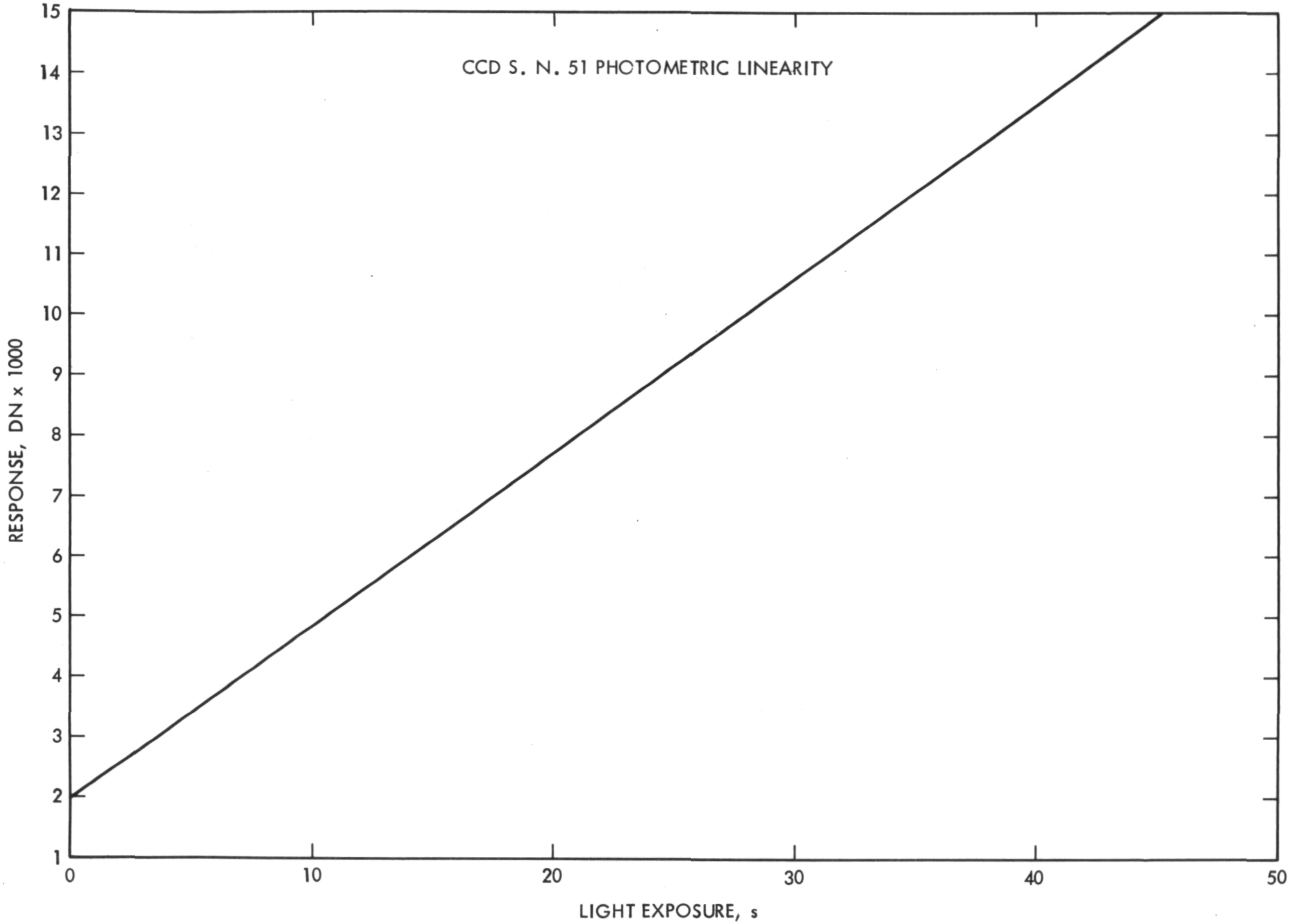

Figure B-1. Response of CCD Measured in Data Numbers. As a function of light exposure the relationship is extremely linear except at low exposure levels, where there is a small but significant deviation

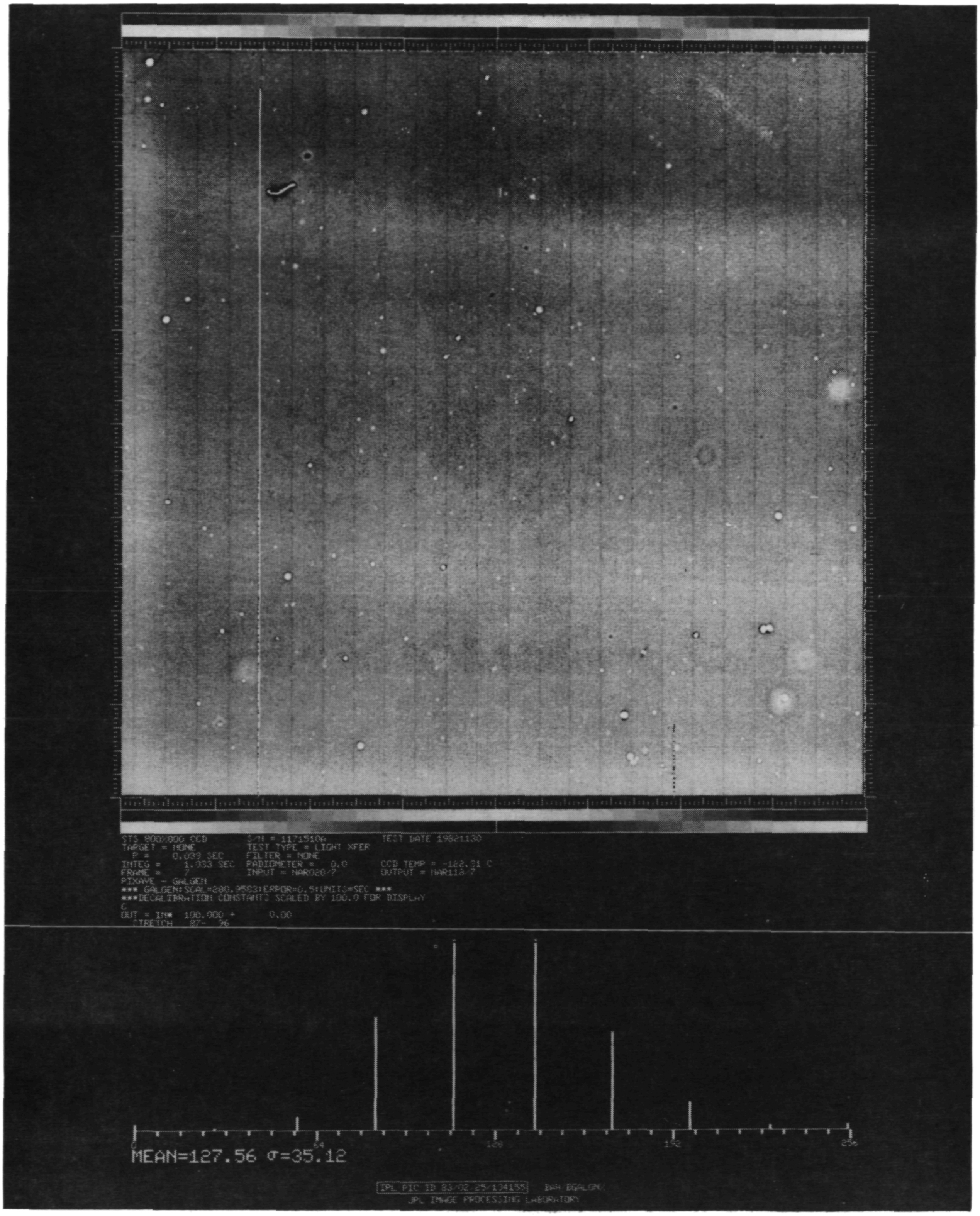

Figure B-2. Image Display of the Decalibration Constants Used to Restore a CCD Image to Photometric Fidelity

B. ALTERNATIVE APPROACHES TO MEASURING THE CONTRAST OF PENSTROKES

Three different approaches of progressively greater complexity were explored for measuring the contrast of penstrokes to parchments from the photometrically corrected images. They are:

(1) No segmentation/histogram moments.

(2) Intensity segmentation/contrast measurement.

(3) Spatial segmentation/contrast measurement.

The terms used in the descriptions above are explained in the glossary. The methods are explained in the following paragraphs and are applied to images that were corrected photometrically as described above. The ink-to-parchment contrast in the PMF document decreases as the wavelength of illumination increases. This fact was used to mimic the fading of ink with time by using images taken at 5000A and 6500A of PMF Area 3 (Figures B-3 and B-4). The contrast difference at these two wavelengths was used to simulate fading of the documents in tests designed to detect fading.

1. No Segmentation/Histogram Moment

In this technique no attempt is made to segment the image into areas of penstrokes and into parchment free of penstrokes. Instead, statistical measurements are made from the histogram of intensity values for an area on the image that includes both ink-free parchment and penstrokes.

A baseline histogram is obtained and a monitoring measurement made at some later date (Figure B-5). The statistical measure of the shape of each histogram is compared to look for changes in contrast.

Measurements made on the pair of images of an identical scene acquired through different spectral filters were analysed. It was shown that one statistic of the histogram - the ratio of the variance to the mean - did change in a manner that corroborated the change in contrast observed by looking at the image (Figure B-6). However, it was not obvious that this difference was more easily detected by the histogram analysis than it was by visual inspection. Moreover, this statistic has no clear-cut relationship to the intensity ratio of penstrokes and surrounding parchment.

Figure B-3. Image of a Portion of the PMF Document in 5000Å Light

Figure B-4. Image of a Portion of the PMF Document in 6500Å Light

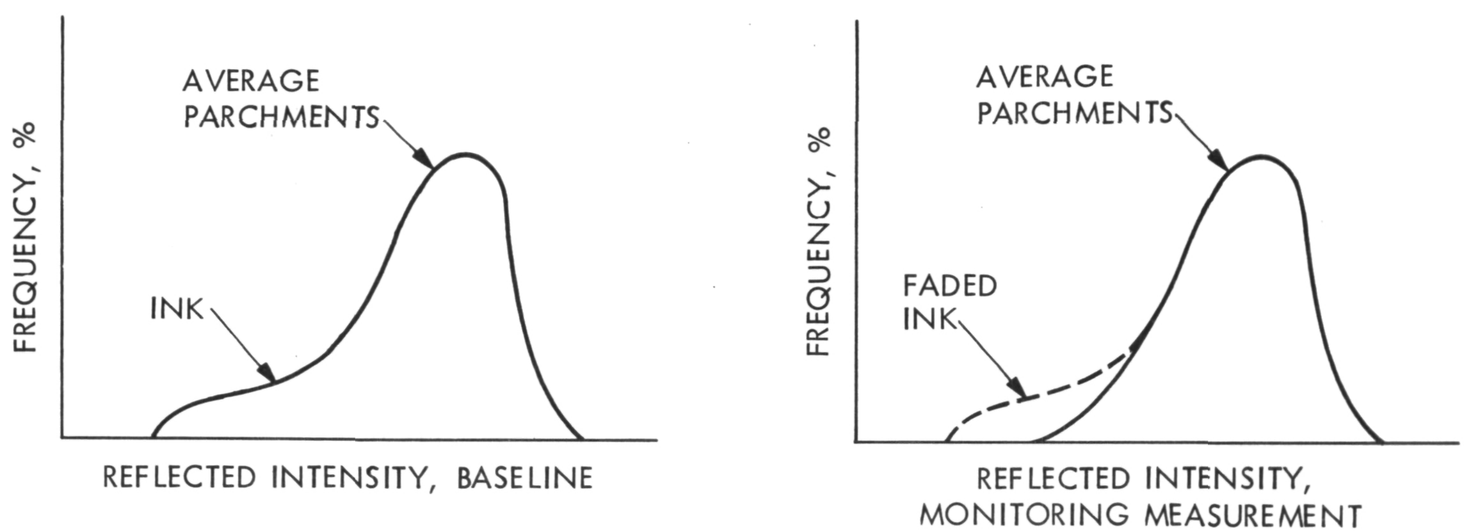

Figure B-5. Measuring Contrast of Penstrokes with a Method Using no Segmentation and Repeated Measurements of Moments of Histograms. In the monitoring measurement (right) the histogram changes because of ink fading. This change is manifested numerically in a change of the higher moments of the histogram.

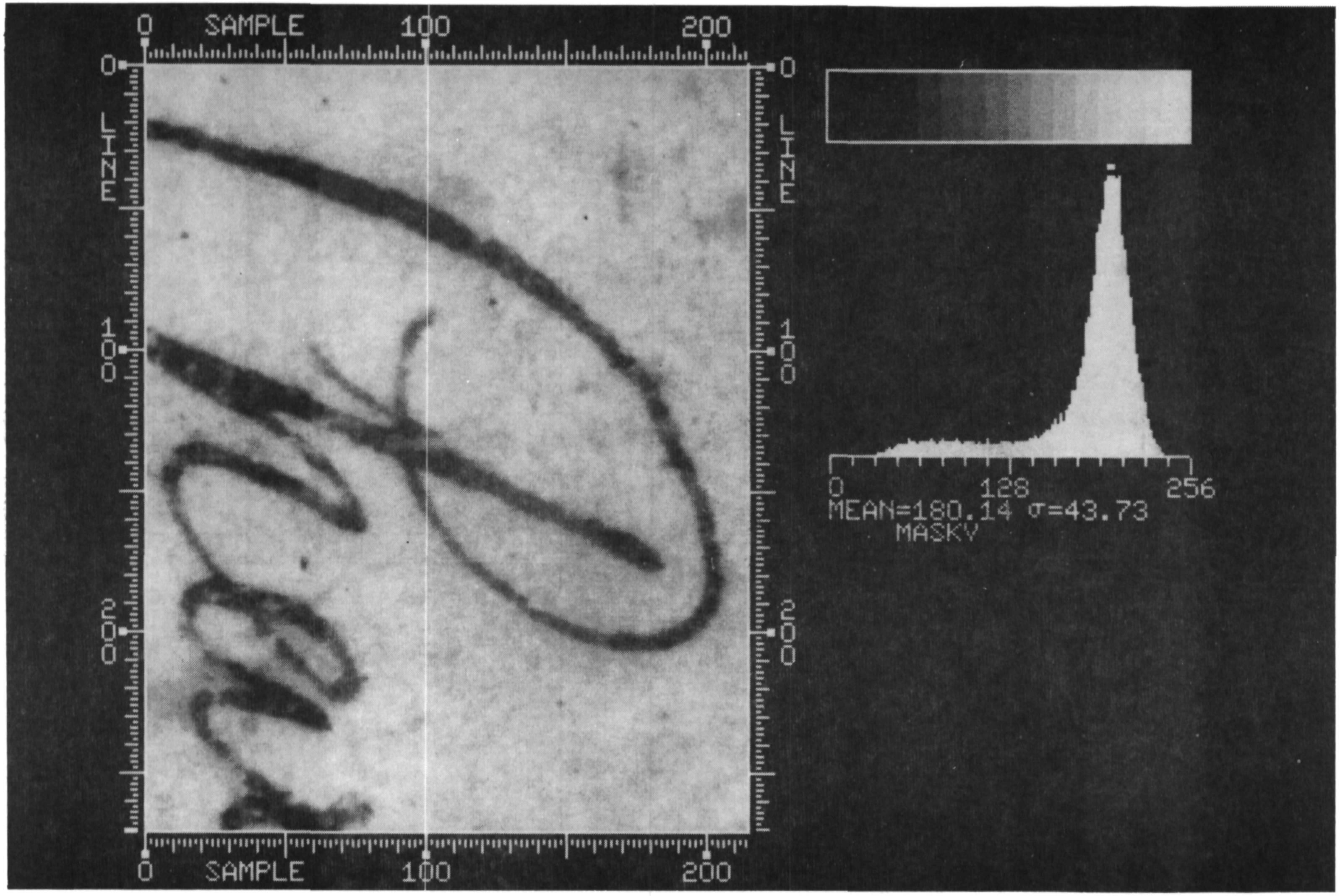

Figure B-6. Segment of an Image of part of the PMF Document (left) and Histogram of the Intensity Values for those Pixels (upper right)

2. Intensity Segmentation/Contrast Measurement

Initial segmentation of the image into areas covered by penstrokes and areas of parchment free of penstrokes overcomes the conceptual problem described above. In the intensity segmentation technique this separation was attempted, using information in histograms alone without reference to spatial relationships. Following segmentation the contrast of penstrokes relative to ink-free parchment is simply calculated. The concept is illustrated in Figure B-7.

To test this method, the curve-fitting capabilities of the HP9845 computer were used. As before, the 5000-Å and 6500-Å images of PMF Area 3 were used to simulate differential fading. Different areas of these images were chosen (Figure B-8) with two goals: (1) Choose areas of bare parchment overlapping areas of parchment and ink to see how the two histograms differ while minimizing the changes in illumination, and (2) Choose two signatures, one that fades with increasing wavelength and one that does not.

The halfword histograms of each of the eight areas in the two images were converted to byte by using the VICAR program LINEAR. A problem was encountered with "picket fencing," or spurious spicks on the curve, due to interpolation errors. An integral number of halfword DNs per byte DN must be used to avoid this problem. The program TERMIST was used to list the histograms. They were then typed by hand into the HP9845 because no easy method of communication (tape or floppy disk) exists.

The histograms are generally not bimodal; they usually show no separate peaks for ink and parchment. They look like an approximately Gaussian, or bell-shaped, curve with the peaks at higher DNs corresponding to the parchment, superimposed on a tail at lower DNs corresponding to the ink. It was hypothesized that the parchment peak could be modeled with a Gaussian curve and subtracted off, leaving the ink histogram. To test this hypothesis, a Gaussian fit in which the mean and the standard deviation were computed was tried for the parchment-only areas. When fitting combined areas of parchment and ink, the resulting Gaussian curve is subtracted from the total histogram to yield the ink histogram.

Contrast is computed by determining the mean of the resulting ink histogram (μi) and using the mean of the parchment (μp) (See Figure B-7) to compute:

$$C = (\mu_p - \mu_i)/\mu_p \tag{B-1}$$

The histogram measure of contrast shows some sensitivity to registration errors. To test the sensitivity, each image was divided into "windows," or areas, composed of a certain number of

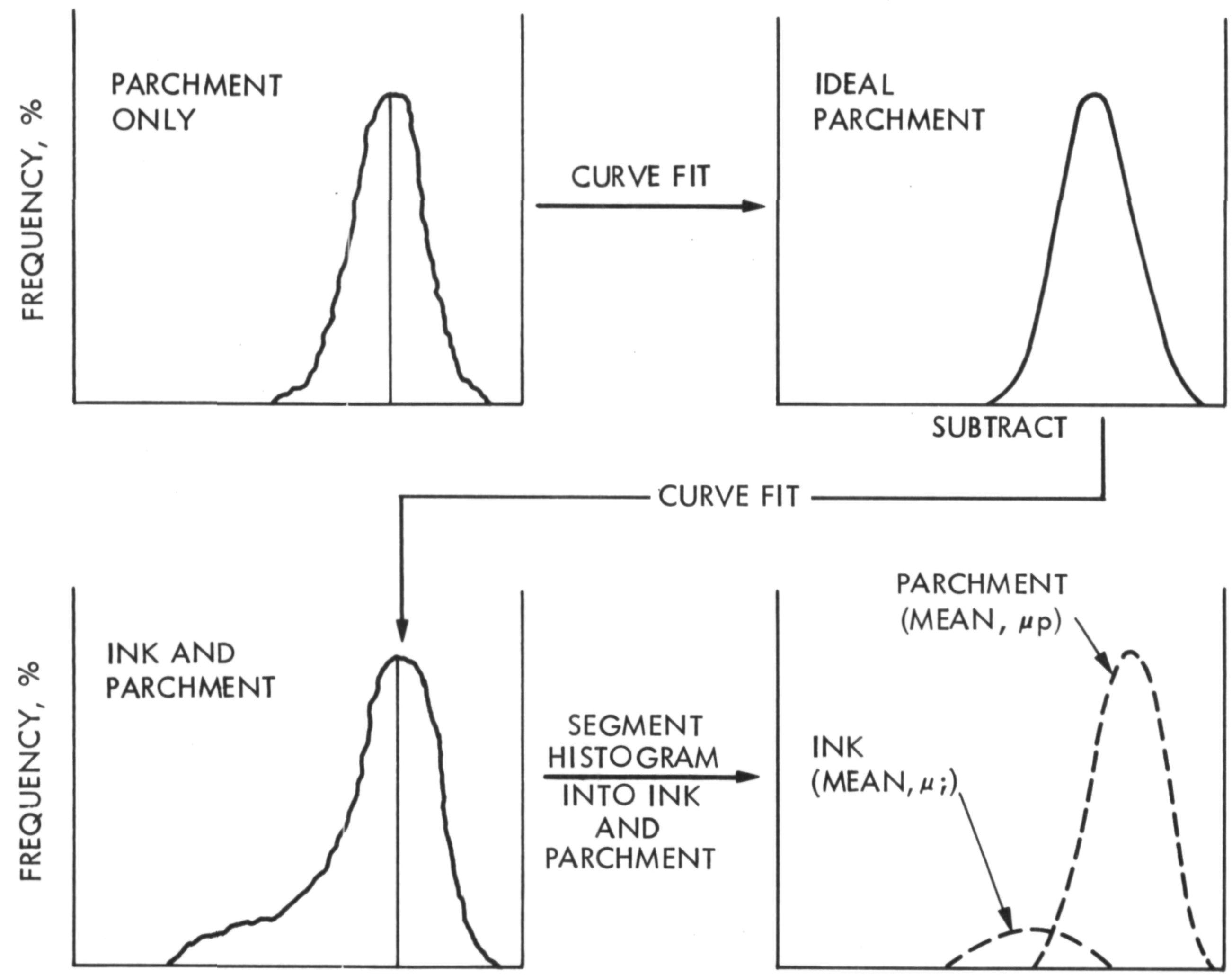

Figure B-7. Measuring Contrast of Penstrokes by Method of Intensity Segmentation Followed by Contrast Measurement

Figure B-8. Areas of PMF Document Used in Test of Intensity Segregation Technique for Measuring Contrast (see Figure B-7)

pixels. Two of these windows, 7 and 8, were used for the test of sensitivity. In the 5000-Å and 6500-Å images the windows were moved in increments of 2, 4, and 6 pixels. The contrast varied monotonically with position for window 8, indicating probably a real change in contrast with position caused by uneven illumination. The contrast varied randomly for window 7. On a contrast scale from 0.0 to 100%, the average difference in computed constrast was: 2-pixel shift, 0.3%; 4-pixel shift, 0.4%; 6-pixel shift, 0.5%. Occasionally, small shifts produced large changes.

A procedure for image registration is outlined later in this section. Precise registration is also necessary for the classifier/mask approach to be discussed. The results of testing indicated the following:

(1) A Gaussian curve is an excellent approximation to the parchment-only histogram, after the very low-amplitude extended tails due to noise are eliminated. As an example, Figure B-9 shows the histogram for Area 3 at 6500Å and the Gaussian fit.

(2) The ink-plus-parchment histograms are typically not bimodel and cannot be trivially separated by thresholding, or identifying all DNs below a cutoff as ink and all those above it as parchment.

(3) The ink-plus-parchment histograms can be separated into their component parts, using the technique discussed above. Figure B-10 shows the histogram for Area 4, which overlaps Area 3 at 6500 Å. Comparing the histogram in Figure B-10 with that in Figure B-9, the long low-intensity tail corresponding to the ink strokes can be seen. The same Gaussian used in Figure B-9 was fit to the data, and a histogram of penstrokes alone was obtained by subtraction (shaded area in Figure B-10). Figure B-11 shows the histogram for Area 7 at 6500 Å. In both figures the raw data, the Gaussian fit, and the subtracted ink histogram are presented.

(4) The technique works well for all but very faded signatures. There is a lower limit to the contrast that can be measured reliably; past this limit the ink histogram increasingly blends with the parchment peak. The contrast trend will anomalously go nonlinear for very faded ink. For example, Figure B-12 shows Area 6 at 5000 Å, while Figure B-13 shows it at 6500 Å. The error in computed contrast for the data in Figure B-13 will be large.

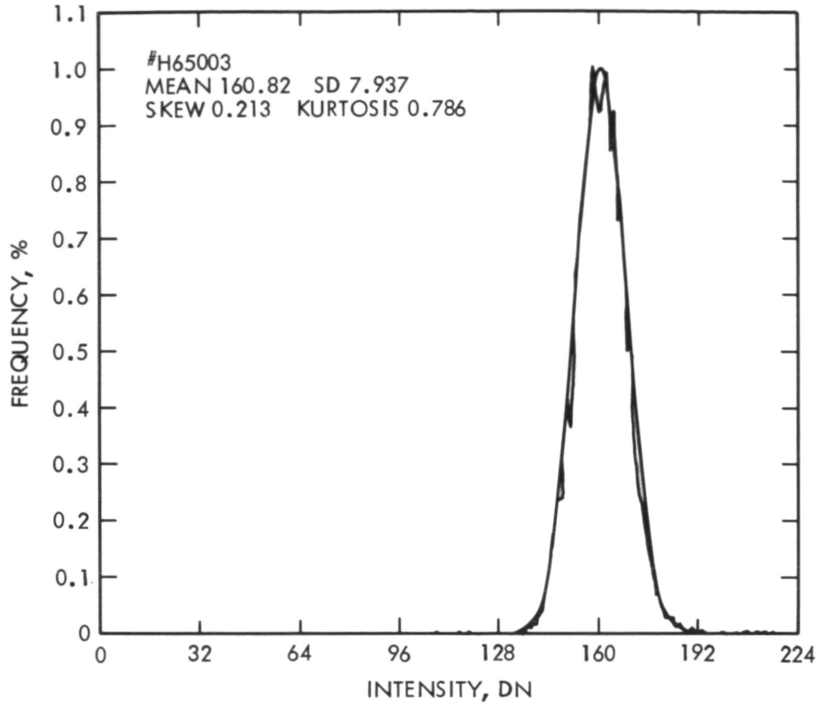

Figure B-9. Histogram of PMF Document Segment Without Ink Strokes Strokes and Gaussian Mathematical Curve that has been set by a Least-squares Method to the Irregular Measured Value

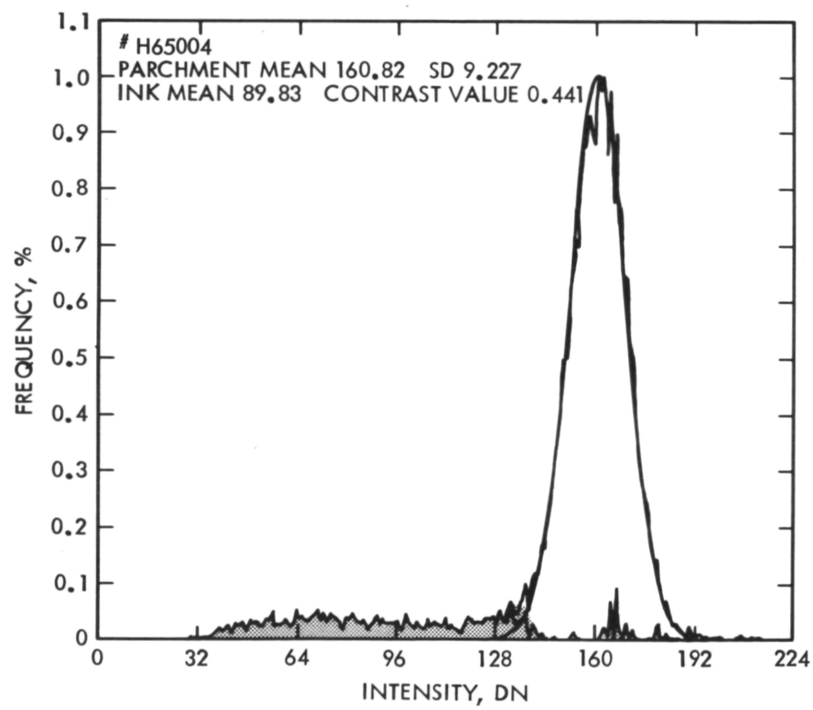

Figure B-10. Histogram of Segment of PMF Document Containing Ink Strokes (Area 4)

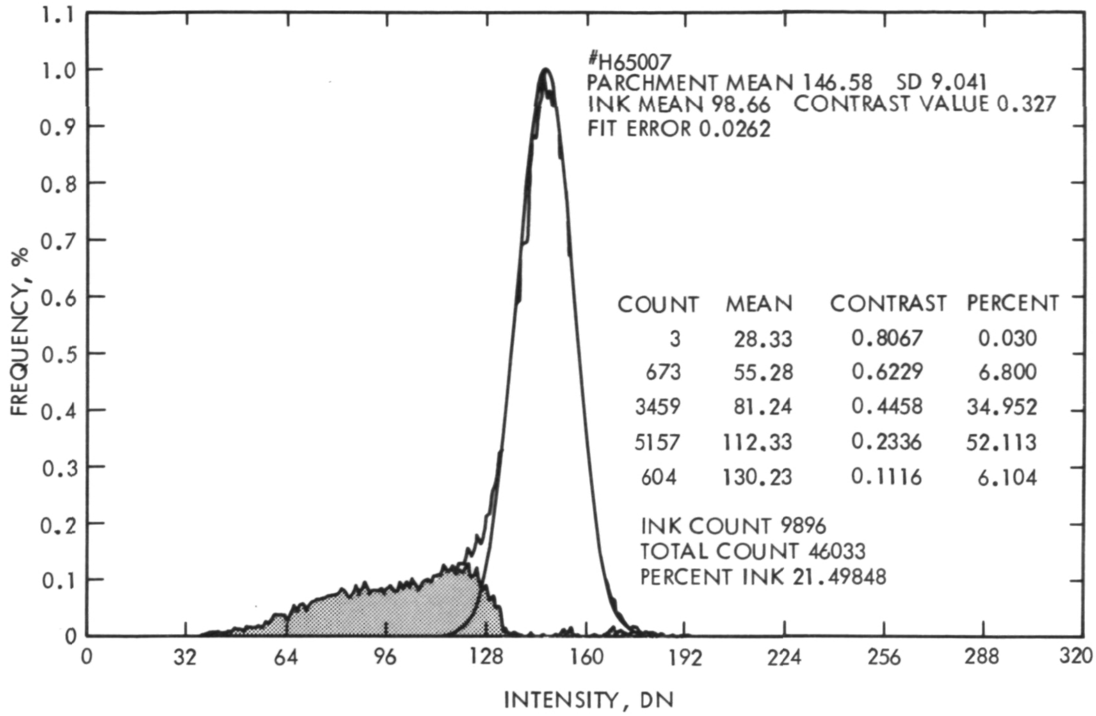

Figure B-11. Histogram for Area 7 in Figure B-4

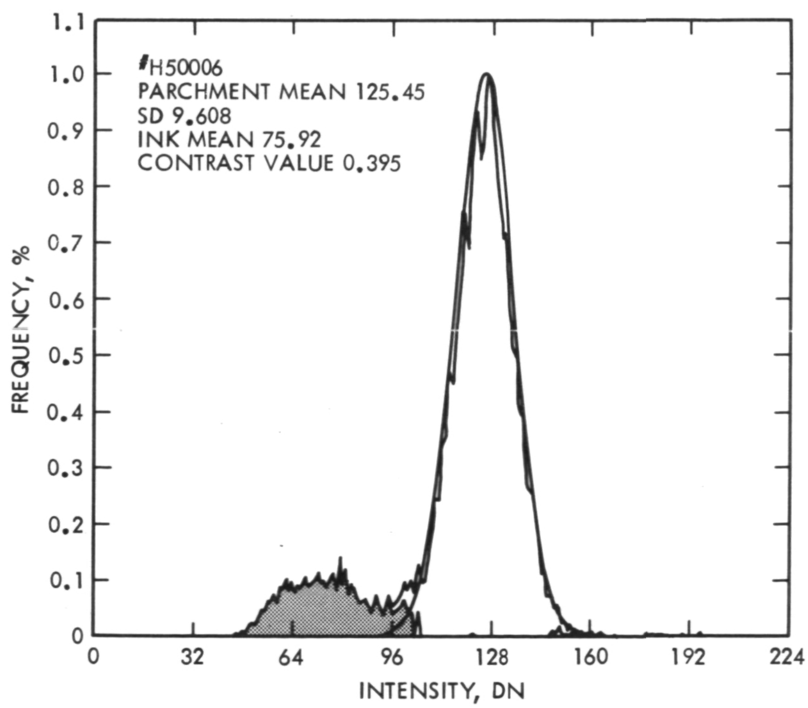

Figure B-12. Histogram for Area 6 at 5000 Å

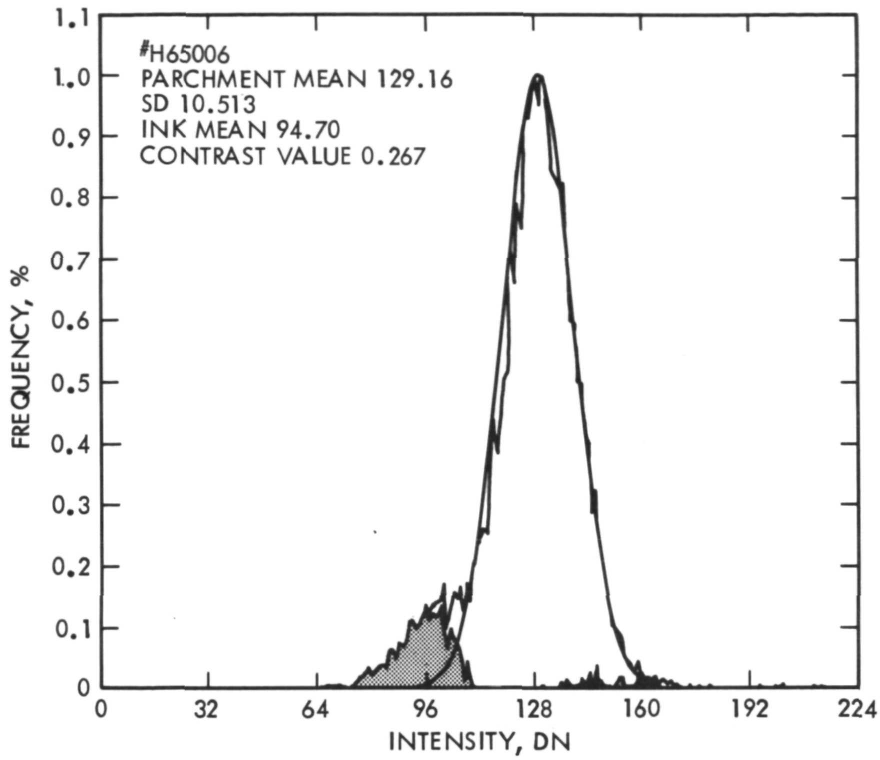

Figure B-13. Histogram for Area 6 at 6500 Å

(5) The above problem can be somewhat alleviated by using normal-incidence illumination in the NARS system, which should suppress the parchment texture and narrow the Gaussian peak.

(6) Areas of reasonably dark ink in the Charters of Freedom should be chosen for application of this technique.

3. Spatial Segmentation/Contrast Measurement

The limitations of the intensity segmentation method lead to the investigation of a more sophisticated technique in which the fact that a penstroke is a region of contiguous inked picture elements (pixels) was explicably taken into account. Two techniques that exploit this property were examined. The least successful is discussed first.

a. Edge Detection/Template Matching Method. The algorithm tested here was originally developed as a biomedical artery tracker used for studying the advance of atherosclerosis in human patients. An analyst identifies a line running down the approximate center of an artery in an X-ray image, with a track-ball and cursor. The algorithm goes out perpendicular to this line and finds the artery. It produces a plot of the edges, a plot of artery diameter vs. linear distance, and plots of the

Figure B-14. Example of Edge Detection in a Section of the Word "Charles" Imaged at 5000 Å

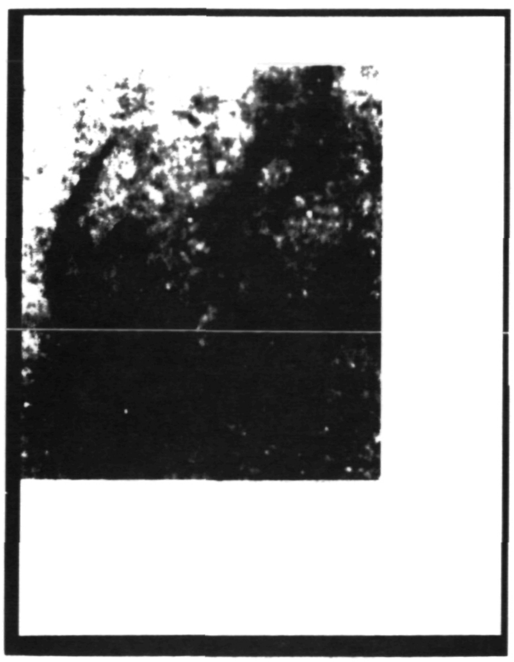

Figure B-15. Example of Edge Detection in a Section of the Word "Robt." Imaged at 6500 Å

slope of the edges. Figures B-14 and B-15 show the results of using this algorithm on carefully chosen, well-behaved penstrokes in "Charles" at 5000 Å and "Robt." at 6500 Å. A sufficient degree of smoothing was applied to prevent the edges from breaking up into noise. The edge might be used as a template to separate ink from parchment. Although the technique appears to work well in these simple cases, experience with edge detectors indicates that the following problems would occur:

(1) In many cases it will be difficult to connect the edges and breakup of the template will occur.

(2) Incorporation of sufficient smoothing to prevent breakup in all cases will result in the inability to track fine-edge detail, resulting in the inclusion of parchment pixels within the template.

(3) Some edge detection algorithms, such as the artery tracker, will not work where penstrokes cross or where they are close together. This might restrict the choice of ink to be monitored to a small fraction of any given 1 x 1-in. CCD image, depending on the algorithm used.

(4) Unlike the PMF, the Constitution consists mostly of writing that is so severely flaked that it looks like a series of disconnected dots. Edge detection may perform very poorly for this document, detecting extraneous lines as well as the dots.

Considering both the many problems associated with this method and the excellent applicability of the multidimensional classification scheme described in the next section, edge detection is not recommended for use in future NARS analysis.

b. <u>Multidimensional Classification/Binary Mask Method</u>. This is the most successful algorithm evaluated to date and discriminates pen strokes from parchment based on measurements of intensity and spatial context. The current implementation illustrated in Figure B-16 uses:

(1) A measure of texture (the autocorrelation function).

(2) An autoregressive model of individual brightness values.

(3) A Bayesian scheme for classifying pixels and blocks of pixels to form templates defining ink and parchment.

After classification of the image into areas of ink (penstrokes) and parchment, the contrast could be measured as defined earlier. For measuring changes, a new image must be registered

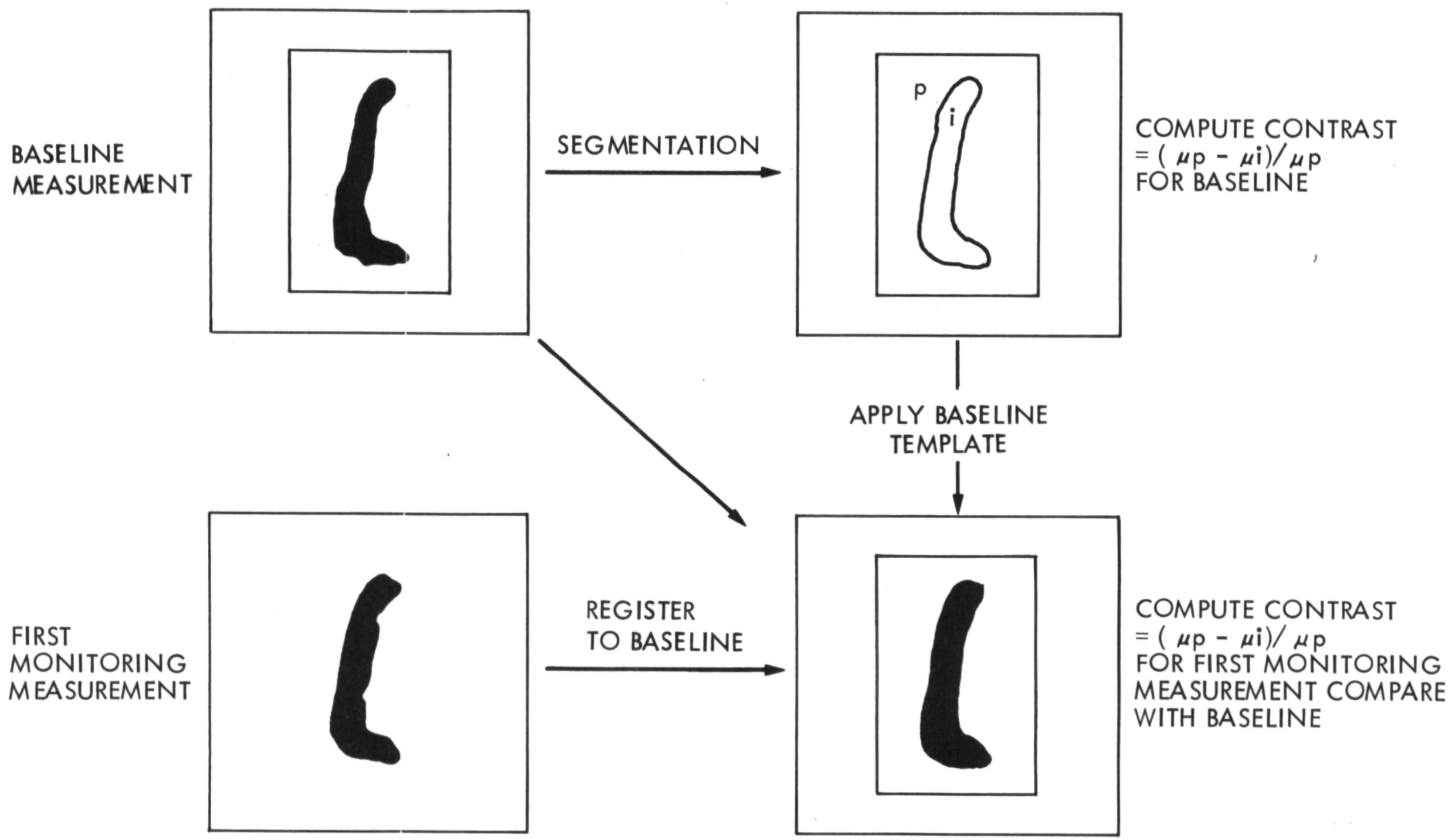

Figure B-16. A Spatial Segmentation Method of Measuring Contrast and Contrast Changes. This is the multidimensional classification/binary mask method

with an old one and the contrast measurement repeated with the old template.

Theoretically, this method should work better than edge detection or other techniques and this was borne out in tests. It was "trained" on small areas of ink and parchment, then used to compute a binary mask for the entire image in which 0 is ink and 255 is parchment. The results are shown in Figures B-17 and B-18.

To date this algorithm appears to be the best for the NARS problem. With proper training, it was able to separate ink from parchment to a high degree of detail in this region. The upper left image is the raw test image, sized up from 500 to 1000 lines/inch spatial resolution with SIZE, a bilinear interpolation routine. The next image (upper center) is the output binary mask, in which 0 = ink and 255 = parchment, superimposed on the raw image. The fit is excellent and requires only a slight amount of fine tuning. (A small amount of parchment and flaked regions are included in the 0 DN mask region, while a small amount of faded ink near the letter edges has been classified as parchment.) To show the degree of fit more clearly, a contour was created around the 0/255 boundary by high-pass filtering the image of the mask with a 3 x 3-in. box size. The contour was thinned to a width of one pixel through the use of a table stretch. The resulting contour is slightly larger than the 0 DN region of the mask, but when superimposed on the image (upper right), it gives a good indication of fit.

The VICAR programs used were AUTOREG for training and CLASSIFY for classification. With better training, the degree of fit could be improved. The basic problem with these images is the narrowness of the penstrokes. Training is performed on rectangular windows whose edges are parallel to the image edges. Training can be improved by use of SIZED-up images and by combining several separate training windows.

To handle the problem of "mixed pixels" (pixels near letter edges whose classification is not clear) the binary mask must be shrunk before defining the ink pixels and grown before defining the parchment pixels. This might be done by "growing" the mask outline and using it as a second mask. The desirability of doing this, in relation to a measure of readability, is under consideration.

C. COMPARISON OF CONTRAST MEASUREMENT APPROACHES A PROPOSED CONTRAST MEASUREMENT FOR NARS

Several approaches to performing contrast measurement on penstrokes are compared in Table B-1. It was apparent that a method utilizing spatial segmentation was most appropriate. A specific procedure is described below.

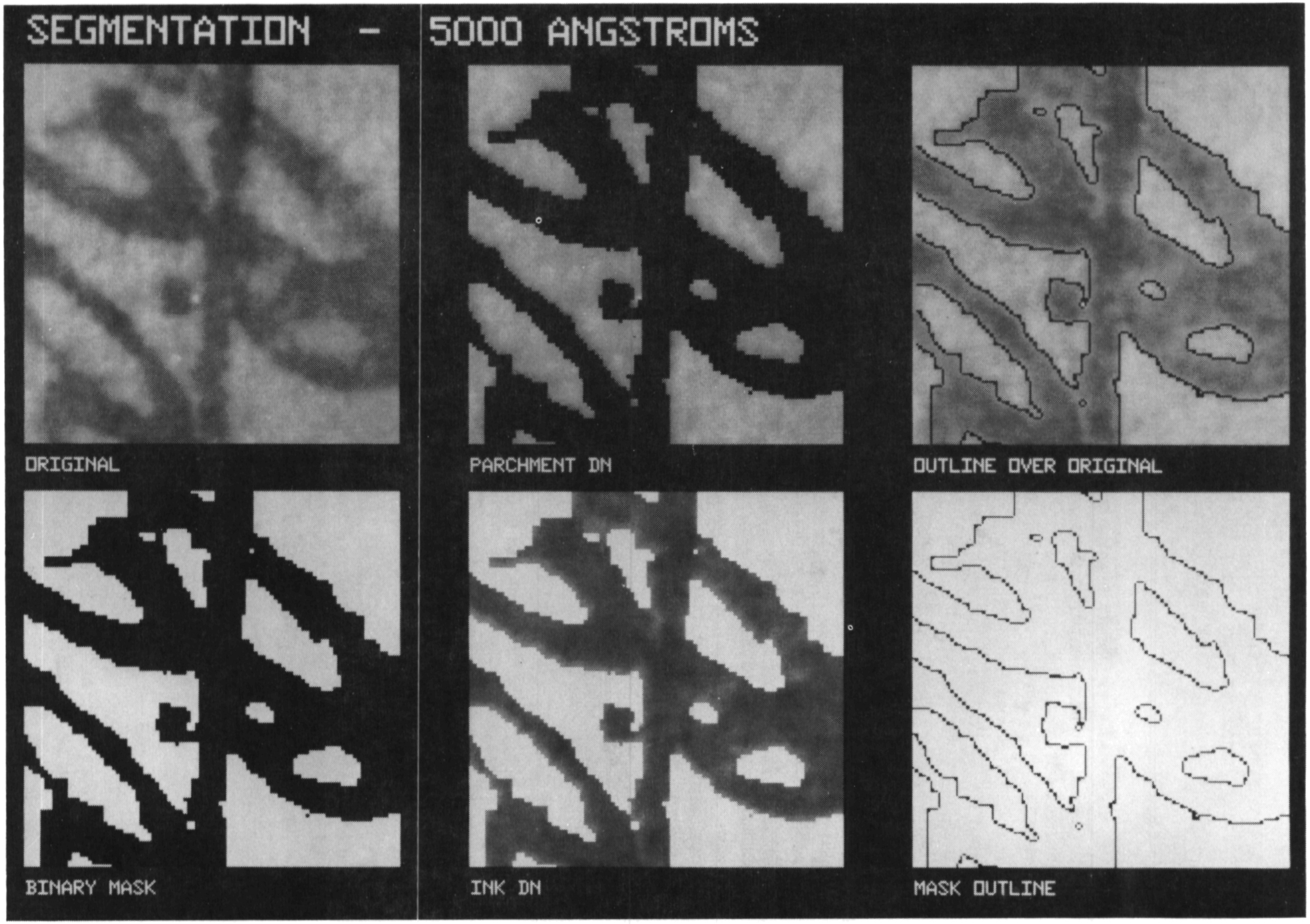

Figure B-17. Application of the Multidimensional Classification/Binary Mask Method Showing Segmentation of the Image into Ink and Parchment (Image Obtained at 5000 Å)

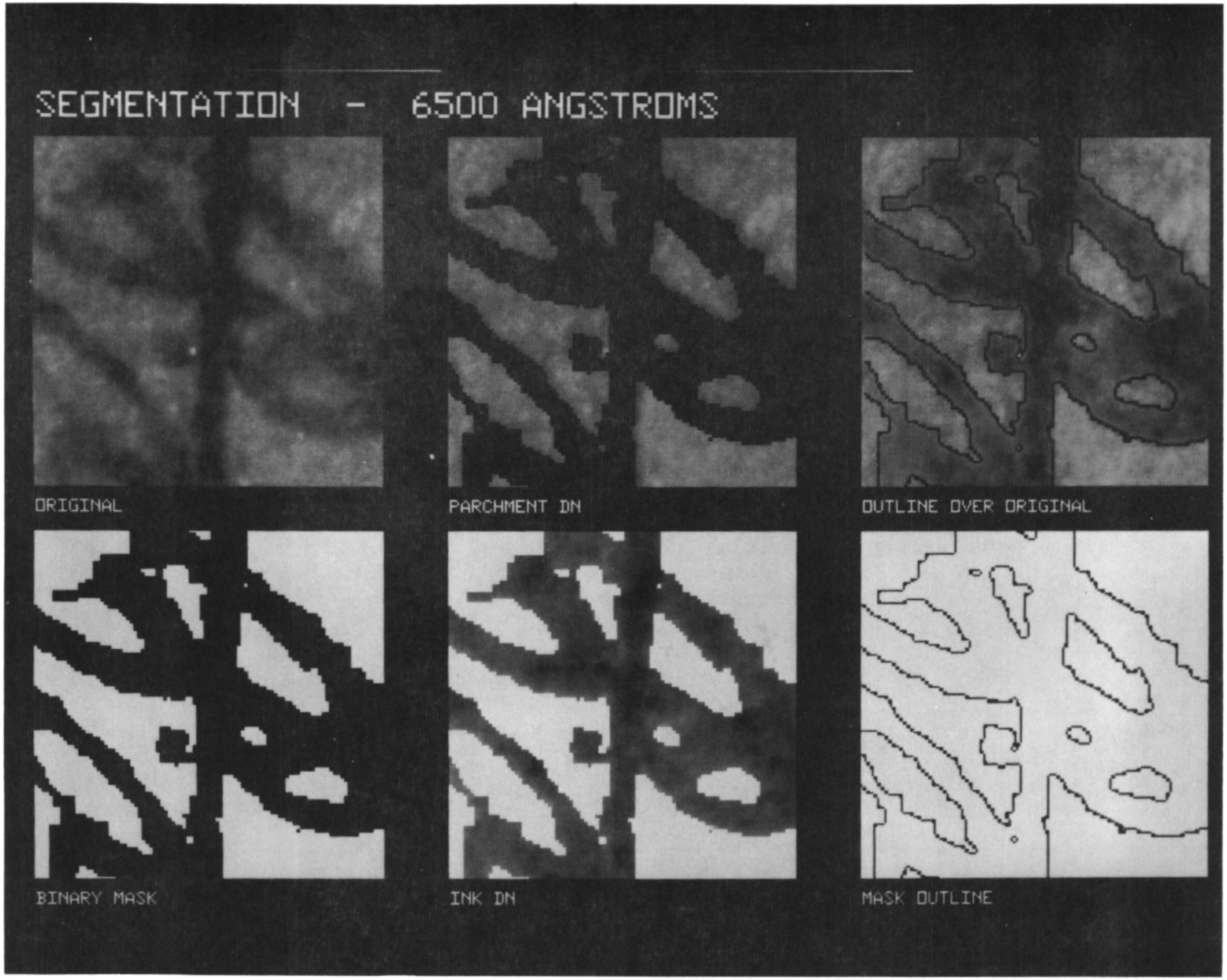

Figure B-18. Application of Multidimensional Classification/Binary Mask Method Showing Segmentation of the Image into Ink and Parchment (Image Obtained at 6500 Å)

Table B-1. Comparison of Alternative Digital Image-Processing Methods for Measuring Deterioration in Readability

Method	Concept	Evaluation: Advantages	Evaluation: Disadvantages
1. No Segmentation/ Histogram Moments	Determine the histogram of an area of parchment and penstrokes	Simplest method	No clearcut definition of contrast
	Compute mean and higher order moments of the data		No insight into what is happening to ink and parchment
	Repeat measurement Compare histograms (subtraction) Compare means and shape measures		
2. Intensity Segmentation/ Contrast Measurement	Calculate the histograms of intensity values for two adjoining areas Parchment only without penstrokes Parchment marked with penstrokes	Simple method Fairly insensitive to registration errors	Measurements of contrast probably no better than 10%
	Fit the parchment-only data with Gaussian curve; determine mean and variance	Potential for further improvement using multispectral segmentation	Will not work well on low-contrast letters
	Perform a best fit of this Gaussian curve with the histogram of parchment marked with penstrokes		
	Subtract the two curves to determine the brightness of penstrokes		
	Calculate contrast of parchment and penstrokes		
	Repeat for subsequent observations of same area		

Table B-1. (Cont'd.)

Method	Concept	Evaluation: Advantages	Evaluation: Disadvantages
3. Spatial[a] Segmentation/ Contrast Measurement	<u>Segmentation</u> Discriminate ink from parchment on the basis of measurements of intensity and spatial context Current implementation uses: A measure of texture (autocorrelation function) An autoregressive model of individual brightness values A Bayesian scheme for classifying pixels and blocks of pixels to form templates defining penstrokes and parchment <u>Contrast Measurement</u> Calculate contrast of parchment and penstrokes <u>Measurement of Change and Trends</u> Register new image with old Repeat contrast measurement using old template	Most accurate method Can also be used to characterize textural changes and ink removal	Requires sophisticated software

[a]The line-segmentation technique described in Appendix B is not described in this table.

1. Recommended Technique

a. Select several regions of the Charters for detailed monitoring.

b. For each region, select algorithm training areas. The selection of new training areas for each new region will allow for differences both between documents and within documents, as well as the inclusion of different types of features (microbial growth, stains, insect damage, etc.).

c. For the NARS baseline, a computer analyst would train the algorithms, run it, and produce a binary mask for each region.

d. Edit each mask empirically to omit anomalies such as flecks of ink in the parchment area.

e. (Modify the mask boundary to omit mixed pixels, as described above. This step is optional.)

f. Use the mask to separate ink pixels from parchment pixels in each image, compute contrast as in Equation B-1, and store the results.

g. Store each mask.

h. For each region monitored, re-image at the next monitoring session.

i. Attempt automatic registration of each "new" image with each "old" image, as described in the next section.

j. If this does not work, use manual registration, as described in the next section.

k. Apply the baseline mask to each new, registered image. Separate ink pixels from parchment pixels and compute contrast.

l. Treat each successive monitoring session in the same manner. Always register with respect to the baseline image and apply the original baseline mask.

The changes in contrast that are measured with the multidimensional classification/binary mask method might be due either to ink fading (and parchment darkening/fading) or to ink flaking. Ink flaking will cause the area within the ink part of the mask to be measured as an average higher DN. It is important that the two effects will be taken if only one of the two types of degradation is detected by the system.

Fading and flaking can be separated through the following modification of the implementationn outlined above, with the obvious limitation that flaking below a certain spatial scale cannot be detected. A brand new binary mask should not be created at every monitoring session because it would be impossible to positively separate changes in the ink from changes in the behavior of the algorithm. The separation of the two effects can be done as follows (continuing the list):

m. After registration, or superimposition of two images, subtract the baseline image from the "new" image. Threshold and stretch the results. Regions of ink flaking will appear as bright patches of contiguous pixels. This concept is illustrated very crudely in Figures B-19 through B-21. Figure B-19 represents the baseline image. In Figure B-20, ink in three selected areas has been digitally flaked off by substituting a small image of parchment. In Figure B-21, the two images have been differenced and the result has been enhanced. Obviously, real changes will appear very differently from the synthetic ones used here, but the concept should be apparent.

n. Crease a copy of the baseline mask.

o. Modify the copy. For all non-zero pixels in that threshold subtraction that fall within the "ink" part of the mask, change the mask value from 0 to 255.

p. Apply the modified mask to the new image and recompute the contrast.

q. Compare the contrast computations made with the baseline and with the modified masks to determine that fraction of the contrast change that is actually caused by fading. Store the results.

r. Treat each successive monitoring session in the same manner. Always use the baseline mask and a new modified mask.

2. Registration Details

The method of contrast measurement outlined above relies on precise registration of a "new" image with an "old" image. There are three possible registration methods, but only one that was found to work with certainty for this task:

a. "Flicker" mode, in which the old and new images are rapidly, alternatively displayed. The user can translate and rotate one image by successive approximation until a "match" is achieved.

Figure B-19. Illustration of Ink-flaking Detection
("Before" Image)

Figure B-20. Image of Figure B-19, Including Artifically Introduced Flakes

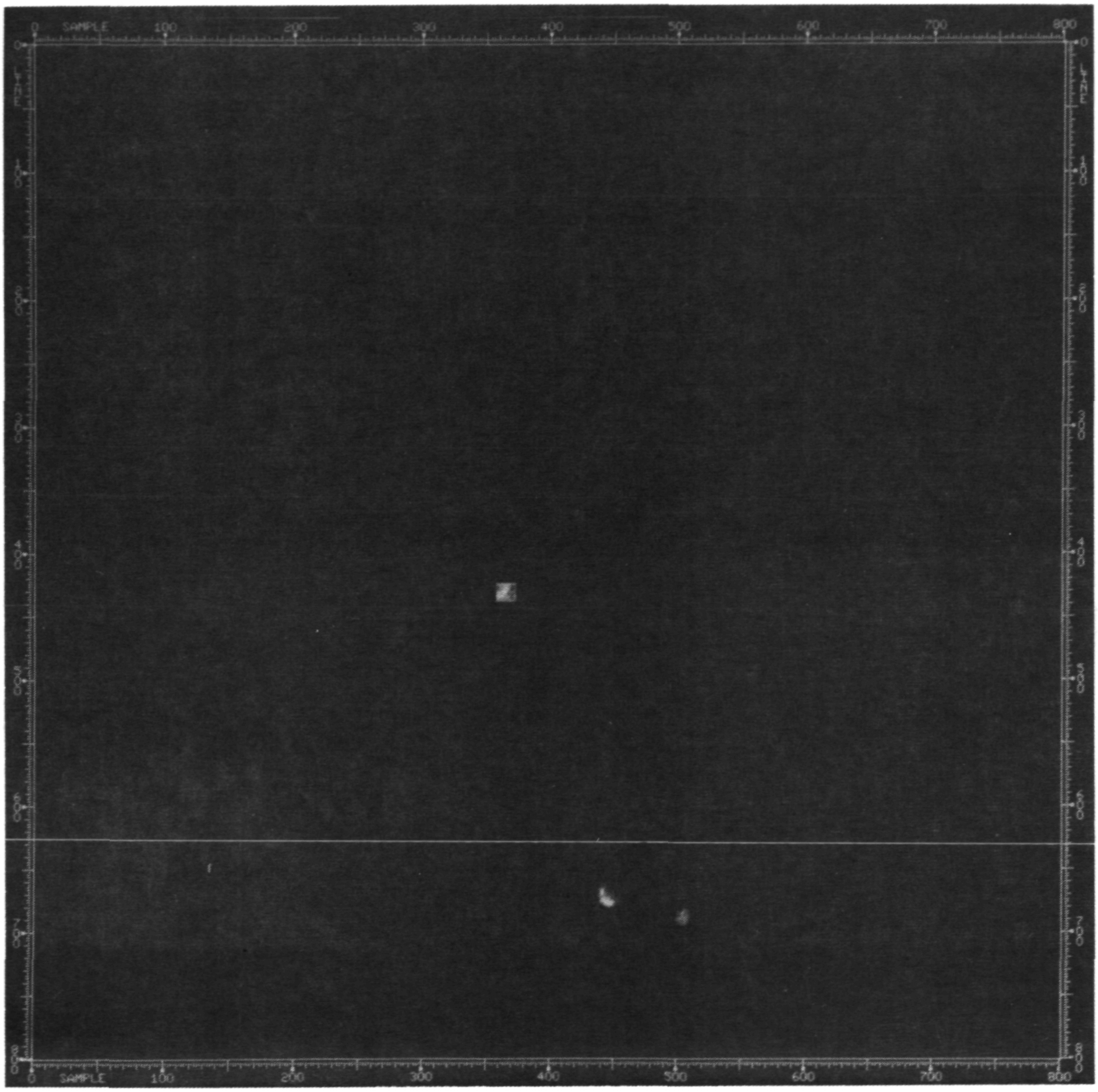

Figure B-21. Subtraction Image from Figures B-19 and B-20
Showing Areas of Change

b. Align the old edge template or mask over the new image with a combination of joystick translation and software rotation of the graphics plane with respect to the image plane.

c. Use the PICREG-GEOM tiepoints approach, in which common points in both images are identified, and one image is geometrically distorted to match the other.

Method 3 is the only one that will account for severe distortion that may be encountered in some circumstances. Two versions of Method 3 could be implemented. The first version involves automatic registration, which can be accomplished if the camera system can be repeatedly aligned over the years on the same letters in the Charters. The second version, a manual registration based on PICREGB/GEOMA, can be implemented if the automatic mode does not work. In practice, its use might not be necessary until a number of decades have elapsed.

When the baseline Charters of Freedom data are acquired, a number of good tiepoints for each area should be selected to be monitored. "Good" tiepoints might be the intersection of two well-defined penstrokes. Later, when the comparison data are taken, the old image and new image will be displayed on monitor, side by side. The selected tiepoints will be displayed over the old image. An analyst will place the cursor at approximately the corresponding position of each tiepoint in the precise locations in the new image. Prompts will also be made to guide the user regarding the reason for bad matches, for example, either (1) the user chose a bad point or (2) the document changes (ink flaked off). The user could easily examine the image for the latter and omit that tiepoint from further use.

It is necessary that this registration activity be carried out in the course of the NARS analysis for the contrast measurement methods to be assured of success.

D. OTHER METHODS OF MEASURING INK FADING

1. Subtraction and Summing

This is a method of detecting fading in which subtraction of registered images acquired at successive monitoring sessions is followed by pixel summing and averaging. As a measure of change it is not recommended for the NARS analysis problem. The change from one session to the next will be very small. Hence, the noise per pixel in the subtracted image will be high. Figure B-22 shows the result of subtracting the 5000-Å "Robt." image from the 6500-Å "Robt." image, as an example of what this technique would produce under ideal conditions. The degree of fading in this example was extreme. A typical Charters subtraction with a time difference of one year would probably appear as only noise.

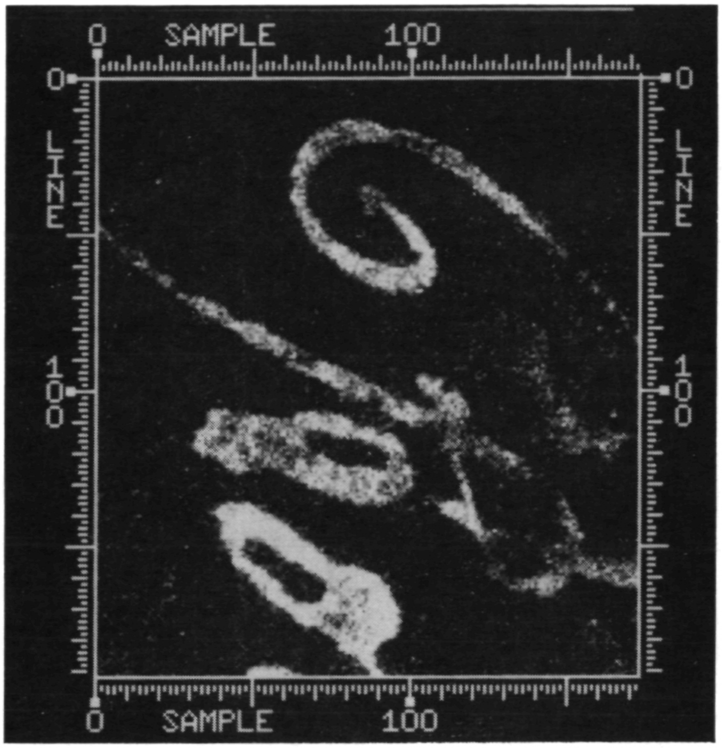

Figure B-22. Image Subtraction Techniques for Detecting Change
(see Text for Details)

2. Multispectral Classification

Multispectral classification is a measurement technique that could use the VICAR program COLORASM to convert three images from color space to hue. saturation, and intensity (H,S,I) space, and note changes over time for the segmented parchment and ink areas. This technique remains to be tested but should probably be included in the NARS analysis.

3. Saturation Ratio Display

The techniques described above measure how much fading is occurring but not where in the image it is occurring. This could be determined in one of two ways. The raw images could be subdivided into a number of bins and statistics derived for each. A method that would be more easily detected by the eye would be to code the local magnitude of the contrast change by DN and display the information as a false-color image on the monitor.

Such an image (use Figure B-23 as a reference), could be created using multispectral images in three bands from successive monitoring sessions. Each set of three images would serve as input for the VICAR program COLORASM, which converts (B,G,R) to (H,S,I), i.e., hue, saturation, and intensity. For our application, different bands would be used for (B,G,R). The saturation image would be created for each set of three images. The two saturation images would be ratioed, enhanced, and the result displayed, using the color lookup table capability for monochromatic images in the chosen display controller (e.g., deAnza). The pattern recognition capabilities of the human eye would then be used to determine where the changes are occurring.

Alternatively, a single false color-coded enhanced ratio of the monochromatic images from two imaging sessions could be displayed.

E. SUMMARY

The recommended methods for detecting ink fading and flaking are summarized below.

(1) Histogram method provides a bulk measure of ink/parchment contrast change resulting from a combination of fading and flaking by curve fitting and statistically analyzing historgrams.

(2) The multidimensional (spatial) classifier provides segmentation of a scene into ink stroke and parchment, through supervised classification and the spatial correlation properties of a pixel with nearby pixels. It can be modified to handle mixed pixels. When combined with thresholded differencing, it has the potential for separating fading from flaking, down to a certain spatial scale. This method requires geometric registration.

(3) Multispectral classification provides a measure of hue and saturation over time for ink and parchment.

(4) Readability measure, as discussed above, is segmentation into ink and parchment followed by contrast computation and is not a measure of legibility of writing. Research and algorithm development might be done in this area of legibility.

(5) Color display gives an indication of where in a scene changes in contrast have occurred, as a guide to the analyst.

Figure B-23. Color can be used to highlight subtle changes much more effectively than black and white display. Here the intensity values in a monochromatic image of the PMF (5000 Å) have been coded in color

APPENDIX C

IMAGE ACQUISITION CAMERA SYSTEM

Described in this appendix is a system for collection of image data to be analyzed later at a remotely located facility such as the JPL Image Processing Laboratory. Functions to be performed are:

(1) Control the camera, lighting, and positioning equipment for image acquisition.

(2) Store the acquired images for transport to the analysis facility.

(3) Monitor the acquired image data to assure that the data has sufficient quality for detailed analysis.

(4) Annotate the stored image data with information necessary for identification and image analysis.

Each of the functions is discussed in more detail in the following paragraphs.

A. CAMERA, LIGHTING, AND POSITION CONTROL

The operations necessary to adjust the camera and lighting, including positioning the camera field of view, are perceived as being manually controlled. Camera positioning may be motorized but controlled by individual switches for the three axes of adjustment. There would not seem to be a need to provide an automatic control or an interface that is controlled through a computer. However, indications of the settings established should be available in an electronic form so that they can be logged with the image. For operational convenience, the data should also be gathered and displayed alphanumerically at one location.

B. IMAGE DATA STORAGE

A primary objective of the image-acquisition system is to store acquired images for transport to an offline, image-processing facility. Magnetic tape is considered the most convenient mechanism for this task. Optical disk memories may prove to have archival storage advantages and should also be considered. Magnetic tape, however, provides a completely satisfactory solution.

C. MONITOR IMAGE QUALITY

Care must be exercised to assure that the image data acquired for transport has sufficient quality to support detailed analysis. Several features are proposed to that end as follows:

(1) The images shall be visually displayed for qualitative viewing.

(2) The data histogram shall be displayed to verify the camera and lighting settings.

(3) Based on the displayed histograms, it shall be possible to stretch the visual data display through manipulation of data transformation tables.

(4) A quantitative evaluation of the data spread shall be provided by a facility to calculate the means, RMS, and standard deviation of the data within a selected area of the image. Evaluations made possible by these functions include numerical focus verification.

D. DATA ANNOTATION

As a minimum, the following engineering data must be included in a header record for each recorded image:

(1) Data and time.

(2) Camera position.

(3) Camera engineering data.

   (a) Exposure time

   (b) Lens opening

   (c) Critical camera parameters such as the sensor temperature for a CCD camera

(4) Lighting position and intensity.

(5) Document description and the operator's description of the image.

Where possible, electronic representations of the engineering data should be provided for display and inclusion in the header record. A keyboard input is also necessary to provide input for those parameters that cannot be conveniently electronically implemented and for inclusion of operator-initiated comments and descriptions.

E. HARDWARE IMPLEMENTATION

Figure C-1 is a block diagram representation of the proposed image acquisition camera system. The system is organized about a central input/out buss. Image data from the camera is transferred directly to a display buffer where it is visually displayed. The display buffer acts as an extension of the control processor providing access to the image data for the required numerical calculations. A display buffer such as the DeAnza IP5500 provides the required capability.

Control processor computation requirements are not critical to the system operation. Important are the facility for presentation of alphanumeric data for display of engineering data and control menus and display of limited graphic data for histogram presentation. Slow speed input/output interfaces are required for control of the display buffer and tape drive and for minimal data transfer to a header buffer and the display buffer data transformation tables. Several small computers such as the "professional" computers being offered by Digital Equipment Corporation, IBM, or Apple would serve the need. Similarly, the tape drive requirements are not stringent. A unit such as the Cipher FS8800 Microstreamer would be appropriate.

Data transfer to tape is initiated from the control processor. The image data, previously loaded into the display buffer memory, now moves directly from the display buffer to the tape drive without buffering in the processor.

Unique designs will be required for several system elements. The header buffer design will be dictated by the form of the camera, positioning, and lighting engineering data. Unique interfaces may also be necessary for the tape drive and the display buffer.

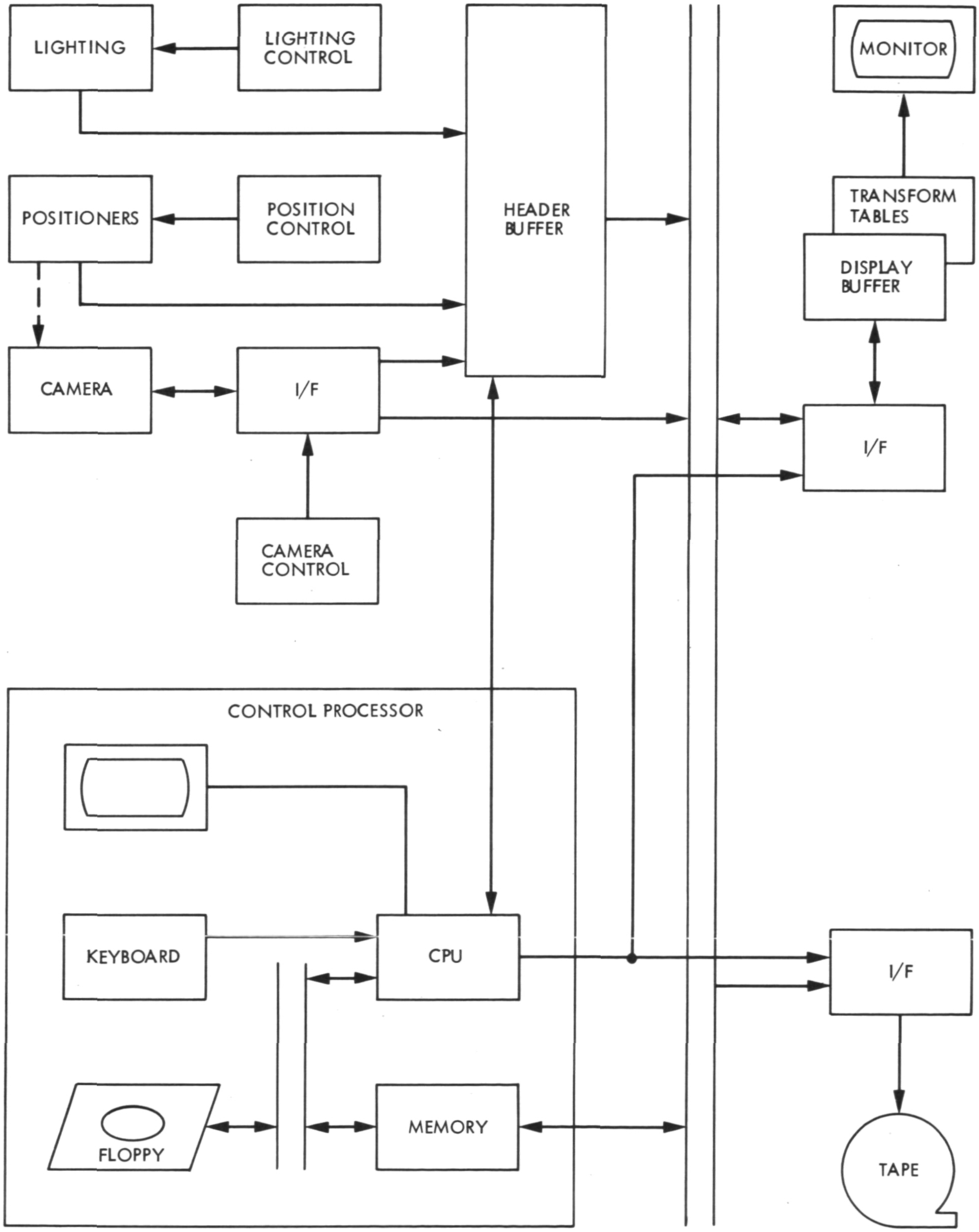

Figure C-1. Image Acquisition System Block Diagram

APPENDIX D

HARDWARE SYSTEMS FOR NARS IMAGE PROCESSING SYSTEM

This appendix describes the results of an evaluation of suitable hardware systems for the National Archives and Records System Charters of Freedom task image processing system to be located at the NARS facility. These systems would potentially meet the requirements of the Option B or Option C concepts discussed in Section VI.

Several of the microprocessors, integrated computer systems, and packaged image processing systems now available have been examined and their suitability for the NARS CoF task studied. Recommendations for the hardware, as well as some proposed point designs using the recommended hardware, are given.

The assumption made in this report is that the desired system, both from the point of view of NARS and of JPL, is one in which the image-processing functions can be performed at NARS, either immediately or eventually. If the desired system is for camera control only, and <u>no</u> image processing functions are desired, then the hardware studied in this report must be re-evaluated in that light.

A. CRITERIA

Microprocessors and packaged systems based on 16- and 32-bit systems were evaluated on the following criteria:

(1) <u>I/O Speed</u>. Many of the processors have a limited I/O speed. The data rate, without buffering, from the NARS CCD camera is estimated to be approximately 500 kilobytes/second (kb/s). Can the processor or system handle these data loading requirements without an (expensive) external buffer? If not, does the reduced cost or other advantages gained by the system justify this added complication?

(2) <u>Processing Speed</u>. Can the processor execute fast enough to handle the image-processing tasks required by the NARS CoF task?

(3) <u>Memory</u>. The NARS image processing programs will require a large amount of main memory, at least 2 megabytes (mb). Can the system support this?

(4) <u>Mass Storage</u>. The NARS CoF task has requirements for large mass storage devices, 300 mb or more, as well as a 1600- or 63250-BPI tape drive. Can the proposed processor/system support these?

(5) Ease of Software Conversion. How easy would it be to convert existing IPL programs to run on the proposed processor/system?

(6) System Integration and Availability. Because the NARS task requires short system and program development times and much of the required image processing software already exists, it is highly undesirable to "homebrew" a microprocessor-based system at IPL. Thus, all of the microprocessors are evaluated on the basis of commercially available systems, ready for "off-the-shelf" delivery, rather than on potential systems that might be produced using the hardware. While this excludes many exciting new designs (such as the IAPX 432, see below) it is the only reasonable approach in an environment where the software must be developed, integrated, and delivered in a reasonable short period of time to end-users unacquainted with (and uninterested in) the "arcana" involved in the design of a new system.

(7) Other Criteria. These include expense of the system (is it justified?), ease of interfacing the CCD camera and display devices. ease of use, support available, etc.

B. MICROPROCESSORS

1. The Intel 8086. IAPX 186, 286 Microprocessors

The Intel 8086 and its advanced versions (the iAPX or "Intel Advanced Processor Architecture" 186 and 286) is the most common 16-bit processor currently on the market, due to the popularity of the IBM personal computer. It is capable of addressing up to 1 mb of physical memory, and up to 16 mb of virtual memory with the Memory Management Unit (MMU) chip. Its execution speed is fast: 0.76 million operations per second (mpo/s) although slower than the 68000.

While it does not have any floating-point instructions itself, the Intel 8087 Arithmetic Coprocessor can be linked to it to provide it with a very fast and powerful set of floating-point and extended integer instructions. The iAPX 186 is equivalent to the 8086 but includes the MMU with an 8086 processor in a single package. The 286 has, additionally, the Intel I/O processor chip in its package.

However, there are currently no 8086-based systems that meet the requirements of the NARS task. The I/O rates on systems such as the IBM PC (which uses the 8088), DEC Rainbow 100, and Morrow Designs are quite slow, less than 300 kb/s. They have primitive,

non-interrupt driven architectures, resulting in very inefficient system utilization and low performance. And, even with the 8087 ACoP, the overall executive speed is low enough to present problems in handling the computations needed for the NARS task. Finally, mass storage devices of the type required by NARS are simply not available currently. The 32-mb Winchester-technology drives are the best available; and tape drives, high density or not, are not available to all.

2. The Motorola 68000 (-1, -2) Microprocessor

Motorola's first 16-bit processor, the 68000 Microprocessor, was designed to compete directly with the Intel 8086 line. It has become one of the more popular chips for OEM systems, due to its simple, flexible architecture and instruction set. It runs somewhat faster than the 8086, up to l.s mpo/s. It does not include any floating-point instructions in its repertoire, and the Motorola Floating Point Processor is designed for use with the 68010 (below), not the 68000.

The 68001 and 68002 are advanced versions of the original 68000, including more advanced memory management hardware and faster execution speeds. The 68000 series can address up to 4 mb of real memory and up to 16 mb of virtual memory.

Because potentially useful systems for NARS exist based on the 68000, they will be evaluated as representative of what can be done with the 68000 line in the section on "Integrated Systems" (see below).

3. The Intel IAPX 432

Intel's newest microprocessor is software-compatible with the iAPX 286. An exciting new design, it incorporates on-chip hardware for arranging multiple 432s in a multiprocessor "array" for parallel processing, apparently with <u>no</u> software intervention required: all multiprocessing is handled in chip hardware and firmware. This is an exciting new design for image-processing applications, but currently there are no commercial systems incorporating it, and shipments are of limited test samples only.

4. The Motorola 68010

The 32-bit counterpart of the 68000, the Motorola 68010, is user (but not system) software compatible with the 6800x. Motorola's Floating Point Processor can be used only with the 68010. The Sun Microsystems Workstation incorporates it and will be taken as representative of 68010-based systems. The Sun Workstation is evaluated in the "Integrated Systems" section.

5. Other Microprocessors

These include the National Semiconductor 16016 and 32032, the Zilog Z8000 and Z80000, and other microprocessors. They suffer from the problems noted above for the other new generation processors: no packaged systems or software available, no hardware support. While all intriguing designs, they are currently unsuitable for use in the NARS system.

6. Summary: Microprocessors

While attractive economically and showing a great deal of future potential, none of the existing microprocessors meet the requirements of the NARS CoF task. They tend toward slow computation rates, minimal current software support, and (especially) low I/O rates. They tend to have primitive or minimal high-level language and program development facilities, making the conversion of the IPL image-processing software a formidable task. There are few packaged systems now available using these processors, and those that exist tend to be for home or business use, unsuitable for computation-intensive scientific tasks. Finally, they have limited expandability, making the upgrading of the NARS system to a full image-processing system difficult.

C. PACKAGED SYSTEMS

This section studies the possibility of using a prepackaged image-processing system, such as those made by Dicomed or Gould/DeAnza, for the NARS CoF task.

Such a system has several disadvantages:

(1) While initially inexpensive, the user is "locked in" to one particular manufacturer and software system once the system is purchased. All expansion (if any, indeed, is possible) must be done by <u>that</u> manufacturer with <u>that</u> hardware.

(2) I/O interfacing is almost always difficult and often impossible. The integration of the CCD camera to a packaged system would be a formidable task.

(3) Conversion of existing IPL software to a packaged system would be difficult and counterproductive. If the software that was supplied by the manufacturer for the packaged system was not sufficient for the NARS task, either the initial CoF task or later expansion code would almost certainly have to be reinvented anew to perform the required processing.

Thus, a packaged system is not recommended for the NARS task.

D. INTEGRATED SYSTEMS

This section describes the integrated systems that were studied.

1. 68000-based Systems

There are several commerically available systems based on the Motorola 68000 line of microprocessors.

2. The Sage IV Computer

The Sage IV computer is manufactured by Sage Computers of Reno, Nevada. Shipments began in January 1983. The quoted specifications of the Sage IV are:

(1) Up to 1 mb of main memory.

(2) Up to 8 users.

(3) Up to 256 mb of Winchester-technology disk storage.

(4) Up to 459 kb/s of maximum transfer rate. No generalized parallel data interfaces are currently available, and the fastest serial interface available for the sage has a maximum transfer rate of 19.2 kilo<u>bits</u>/second.

(5) Up to 1.0 mop/s, up to 10,000 floating-point operations per second.

(6) Available software: the UCSD p-System, UNIX, CP/M-68K.

While an interesting system, and well suited to certain applications, the Sage IV is not a recommended system for NARS CoF. It has limited main memory, very limited disk storage, and relatively slow execution speed. The <u>maximum</u> I/O speed is too slow for the NARS CoF CCD camera, and no interfaces are currently available that can exploit even this limited I/O rate. Those interfaces that <u>are</u> available have the quite limited I/O rate of 19.2 kilobits/second or 54.8 kb/s.

The floating-point processing speed is slow, as all floating points must be simulated in software. The available software, while exceptional for a microcomputer system, is none the less limited and slow for the requirements of NARS. The UCSD p-System, while well integrated, is quite slow (as all programs run on a

simulated "p-Machine", rather than the native code of 68000 itself), and the other software offerings have their own disadvantages (UNIX has only a C compiler currently available, and to date there is almost no support software available for CP/M-68K).

Thus, the Sage IV is not recommended for NARS CoF.

3. The Charles River Data Systems Computer

The quoted specifications of the the Charles River Data Systems (CRDS) computer system are quite similar to those of the Sage IV: same amount of memory, same I/O rates, somewhat larger disk storage (up to 640 mb), somewhat faster execution speed. The quoted floating point speed is 0.5 mflop/s, but that quotation is based on the (incorrect) assumption that the Motorola Floating Point Procesor will operate with the 68000; it will not. Thus, the CRDS system is also not recommended for the NARS CoF task, for the same reasons noted above for the Sage IV computer.

4. The Sun Microsystems Workstation

The Sun Microsystems Workstation is based on the Motorola 68010 32-bit microprocessor. It includes 1 mb of main memory and a 1024X800 1-bit/pixel graphics system, used as the system monitor. The system may be upgraded to include up to 2 mb of main memory and 258 mb of disk storage. These are all single-user systems; a multi-user system is built by adding Sun Workstations connected by an Ethernet.

There are several disadvantages to this design:

(1) It is a new, unproven design. It has been in the field only since March 1983, not enough time to evaluate the hidden problems with a design such as this.

(2) While none of the specifications give data transfer rates, it uses the multibus as its backplane connector. The multibus has a maximum transfer rate of 0.9 mb/s, so it is doubtful that an interface card could be constructed to handle the CCD cameras requirements.

(3) The system workstation display is unsuitable for the NARS display device, so another display device would be added. The difficulty of interfacing such a device is unknown and could be a considerable problem when dealing with such a new and unfamiliar design.

(4) Finally, for the amount of support and software that it delivers, the Sun Workstation is expensive. A system with one workstation (single user), 2 mb of main memory, 256 mb of disk storage, and a 1600-BPI tape drive (6250-BPI drives are not available) lists for $57,000; a Sun

Network system that can support two users (two workstations) lists for $84,300, plus field installation charges and miscellaneous hardware (racks, cables, etc.).

The Sun Microsystems Workstation is, therefore, not recommended for NARS.

5. Mainframe Computers

This section evaluates "miscellaneous" mainframe systems, such as for Gould/SEL 32/87 and the Data General "Eagle," as potential systems for NARS.

These systems meet the requirements of the NARS task in terms of computation rates, I/O rates, and available mass storage. While by no means bad systems, they suffer from being of comparable price and utility to systems such as the VAX, which have many intrinsic advantages that these systems lack. To purchase such a system would gain nothing in terms of computer power and lose quite a bit in terms of system utility and ease of software development. Thus, these systems are not recommended for NARS.

6. The DEC VAX Series

The Digital Equipment Corporation VAX series is the final system to be studied. This is the architecture selected for the MIPL project; a VAX 11/780 will be IPL's main computer by April 1984.

The quoted specifications of the lower-end VAX product line (the VAX 11/730 and 11/750) are:

(1) 1 to 4 mb of main memory.

(2) 450+ mb of disk storage in most configurations.

(3) 1600- BPI tape drives standard. 6250-BPI tape drives available for the 11/750.

(4) A maximum transfer rate of 1.2 mb/s on the Unibus and of 10.0 mb/s on the Synchronous Backplane Interconnect (the main VAX bus).

(5) 2 million operations per second, 1 mflop/s.

The VAX 11/730 and 11/750 systems meet all the requirements for the NARS CoF task and have many other intrinsic advantages over comparable systems.

D. SUMMARY: INTEGRATED SYSTEMS

An integrated system has the potential for meeting the requirements of the NARS CoF task, and the mainframe-class systems do meet these requirements. The VAX product line has many intrinsic advantages and no real disadvantages when compared to other adequate systems.

E. RECOMMENDATIONS

The recommended system, based on these hardware studies, is a Digital Equipment Corporation VAX 11/730 or 11/750. The larger machines, the VAX 11/780 or 11/782, are quite expensive and would be "overkill" for the NARS CoF task. Example recommended VAX designs are listed below.

F. POINT-SYSTEM DESIGNS

The following are proposed "point designs" for the NARS system based on the recommended hardware.[1]

1. VAX 11/730 system (SV-CXWMA), includes a 121 MB fixed-media system disk, an additional 456-mb disk drive (RUAB1), 10.4 cartridge disk, floating point accelerator (FP730), 2-mb main memory (1 MSD730-CA), 1600-BPI tape drive (TS11), interface for CCD camera (DR11-W), line printer (LN01), 1-user terminal (VT101). Total price: $92,900; total monthly support: $982. This system <u>cannot</u> support any additional tape drives, the higher-speed interface to the CCD camera (see below), or the DECNet Interface. This system is, thus, recommended only if the budget does not allow for a larger system.

2. VAX 11/750 system (SV-BXEDA), includes 456 MB system disk, low-speed, 1600-BPI tape drive, 3-mb main memory and floating point accelerator (EV75VD-DZ), interface for CCD camera (DR11-W), line printer (LN01), 1-user terminal (VT-101). Total price: $93,250; total monthly support: $861. Note that this system, due to the lower maintenance cost, would cost less than the above 11/730 system after only three months of operations.

3. VAX 11/750 system (SV-BXEDA), includes 456-MB system disk, high-speed, 1600-BPI tape drive, 4-mb main memory and floating point accelerator (EV75VD-DZ), interface for CCD camera (DR11-W), line printer (LN01), 1-user terminal (VT-101). Total price: $119,900; total monthly support: $1,115.

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[1] Costs cited in this section are approximate estimates valid at at the time this information was completed in July 1983.

4. VAX 11/750 system (SV-BXECA), as above except with high-speed, 6250/1600-BPI tape drive. Total price: $132,900; total monthly support: $1,196.

These prices reflect the 35% GSA discount under Digital Equipment Corporation's GSA supply schedule.

An additional 456-mb disk drive can be added to the 11/750 systems above for an additional $12,350 purchase price and $800/month maintenance. This is strongly recommended as there will be a large amount of system and user software to be accommodated on the NARS system. All of the aforementioned systems include a license for the VAX FORTRAN compiler, a C compiler; (the language TAE is written in) would be an additional $2,925.

All of the above point systems include the DR11-W general purpose parallel interface for use as the CCD camera interface. This has a nominal transfer rate of 1 mb/s. If this is not adequate for NARS purposes, the 11/750 systems can substitute the DR750 high-speed intelligent interface, with a transfer speed of 3.2 mb/s, for a total of $3,480 and $44/month extra support charge. The VAX 11/730 cannot support the DR750.

To include one of these systems on a DECNet, as discussed above, requires the DMR11 single-line synchronous interface and DECNet software (ZDD03), for a total of $6,760 and $39/month extra support charge. The 11/730 system cannot be configured in this way.

APPENDIX E

GLOSSARY[1]

Algorithm	A mathematical procedure in a form easily implemented on a computer. Examples are algorithms for computing the decalibrated value of a pixel or segmenting an image into ink and parchment.
Application Program	(See Section V)
Baseline	The first definitive measurement on the Charters of Freedom conducted with particular care, against which subsequent measurements will be referred.
Calibration	A characterization of the distinctive response of a sensor.
Decalibration	The application of calibration data on a sensor to the image of a scene to generate an ideal image without photometric or geometric distortion.
Executive	(See Section V)
Histogram	A compilation of the frequency of occurrence of the brightness levels of pixels in a digital image.
Operating System	(See Section V)
Pixel	Abbreviation for a picture element, i.e., a single resolution element of a picture whose intensity is denoted by a number generally between 0 (black) and 255 (white).
Registration	The process of fitting two digital images together so that the details in each image overlay as closely as possible.
Segmentation	A classification of pixels into groups based on their intensity values and possibly their spatial relationships with the intensity values of other pixels.

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[1] This glossary describes the meaning of terms as they are used in this document. Many of the terms have much broader meanings than those given above.